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DAM SAFETY PROGRAM
STATE-OF-THE-ART REVIEW OF
DAM MONITORING SYSTEMS

Report No 88-298-K

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ABSTRACT

A review of the dam monitoring practices of the foremost dam building countries/utilities of the world has been completed. Information has been provided on the parameters monitored, the people responsible for monitoring, the types of instruments installed, the frequency of monitoring, and where possible, the performance of the monitoring system and of individual instruments. General practice seems to dictate the installation of at least some instrumentation in all large dams, with great emphasis placed on the value of visual inspection. Small dams seem to be monitored primarily by visual inspection only, with basic instrumentation installed if the dam falls into a "high risk" category or if a potential failure is likely. This report provides information on the monitoring practices for "large dams" (ie those satisfying one of the ICOLD criteria). Generally, emphasis seems to be placed on the measurement of seepage, displacements, and pore pressures. These respective parameters are most commonly measured by use of weirs, pendulums and geodetic surveys, and various types of piezometers. Although the frequency of monitoring is site specific, instrument readings are usually taken by regional or local personnel, and sent to a central processing centre where the results are reviewed and analyzed.

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TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	NORWAY	2
	2.1 Philosophy	2
	2.2 Instruments	3
	2.2.1 Surface Deformations	3
	2.2.2 Internal Deformations	3
	2.2.3 Seepage	3
	2.2.4 Pore Water Pressure	4
	2.2.5 Total Pressure	4
	2.3 Measurement	4
	2.4 Performance	4
	2.5 Case Studies	4
3.0	SWITZERLAND	5
	3.1 Philosophy	5
	3.2 Instruments	6
	3.2.1 Surface Deformations	7
	3.2.2 Internal Deformations	7
	3.2.3 Reservoir Water Level	7
	3.2.4 Seepage	7
	3.2.5 Pore Pressure (Embankment Dams)	8
	3.2.6 Uplift Pressure (Concrete Dams)	8
	3.2.7 Temperatures - (Concrete Dams)	8
	3.3 Measurement	8
	3.4 Performance	9
	3.5 Case Studies	9
4.0	UNITED STATES	9
	4.1 Philosophy	9
	4.2 Instruments	10
	4.2.1 Surface Deformations	10
	4.2.2 Internal Deformations	10
	4.2.3 Seepage	11
	4.2.4 Pore Pressure	11
	4.2.5 Total Pressure	11
	4.2.6 Seismicity	11
	4.2.7 Water Quality	12
	4.3 Measurement	12
	4.4 Performance	13
	4.5 Case Studies	13

TABLE OF CONTENTS (cont'd)

		Page
5.0	AUSTRALIA	14
	5.1 Philosophy	14
	5.2 Instruments	15
	5.2.1 Concrete Dams	15
	5.2.1.1 Surface Deformations	15
	5.2.1.2 Internal Deformations	16
	5.2.1.3 Seepage	16
	5.2.1.4 Uplift Pressures	17
	5.2.1.5 Total Stress	17
	5.2.1.6 Temperature	17
	5.2.2 Fill Dams	18
	5.2.2.1 Surface Deformations	18
	5.2.2.2 Internal Deformations	18
	5.2.2.3 Seepage	19
	5.2.2.4 Pore Pressure	19
	5.2.2.5 Total Stress	19
	5.2.3 Concrete and Fill Dams	20
	5.2.3.1 Seismicity	20
	5.2.3.2 Chemical and Biological Analysis of Seepage Water	20
	5.3 Measurement	20
	5.4 Performance and Case Studies	21
6.0	GREAT BRITAIN	21
	6.1 Philosophy	21
	6.2 Instruments	22
	6.2.1 Surface Deformations	22
	6.2.2 Internal Deformations	23
	6.2.3 Settlement	23
	6.2.4 Seepage	23
	6.2.5 Pore Pressure	23
	6.2.6 Total Pressure	23
	6.3 Measurement	24
	6.4 Performance	24
7.0	FRANCE	24
	7.1 Philosophy	24
	7.2 Instruments	25
	7.2.1 Surface Deformations	25
	7.2.2 Internal Deformations	25
	7.2.3 Pore Pressures	26
	7.2.4 Poorly Documented Items	26
	7.3 Measurement	26
	7.4 Performance	26

TABLE OF CONTENTS (cont'd)

	Page
8.0 HYDRO QUEBEC	27
8.1 Philosophy	27
8.2 Instruments	28
8.2.1 Surface Deformations	28
8.2.2 Internal Deformations	28
8.2.3 Seepage	29
8.2.4 Pore Water Pressure	29
8.2.5 Total Pressure	29
8.2.6 Temperatures	29
8.2.7 Seismicity	29
8.3 Measurement	29
9.0 BC HYDRO	30
9.1 Philosophy	30
9.2 Instruments	31
9.2.1 Surface Deformations	31
9.2.2 Internal Deformations	31
9.2.3 Seepage	31
9.2.4 Pore Pressure	31
9.2.5 Total Pressure	31
9.2.6 Seismicity	31
9.3 Measurement	31
9.4 Performance	32
10.0 ONTARIO HYDRO	32
10.1 Philosophy	32
10.2 Instruments	33
10.2.1 Surface Deformations	33
10.2.2 Internal Deformations	33
10.2.3 Seepage	33
10.2.4 Pore Pressure	33
10.2.5 Total Pressure	34
10.2.6 Water Quality	34
10.2.7 Seismicity	34
10.2.8 Temperature	34
10.2.9 Water Level	34
10.3 Measurement	34
10.4 Performance	35
11.0 SUMMARY OF GENERAL TRENDS	35
11.1 Philosophy	35
11.2 Instruments	36
11.3 Measurements	37
12.0 RECOMMENDATIONS	37
13.0 CONCLUSIONS	39

TABLE OF CONTENTS (cont'd)

	Page
REFERENCES	40
TABLES I TO XXVIII	43
FIGURE 1	75
APPENDIX I	76
APPENDIX II	79
DISTRIBUTION	last page

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DAM SAFETY PROGRAM
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R.R. Boothby

1.0 INTRODUCTION

As part of Ontario Hydro's Dam Safety Program, the Soil Sciences Section of the Civil Research Department has conducted an investigation of the dam instrumentation practices in several other utilities and countries. The intent of this report is to provide sufficient information to allow a reasonable evaluation of the adequacy/inadequacy of the existing instrumentation in Ontario Hydro's dams, with special emphasis placed on older dams.

Only "large" dams, as defined by the International Commission on Large Dams (ICOLD), are included in the report because the behaviour of small dams seems to be primarily monitored by visual inspection and not by instrumentation. ICOLD considers a dam to be large if:

1. the height of the dam is above 15 m, measured from the lowest portion of the general foundation area to the crest,

2. the height of the dam is between 10 m and 15 m and at least one of the following criteria is satisfied:

   a) crest length $\geq$ 500 m,
   b) reservoir capacity $\geq$ 1,000,000 cubic metres,
   c) maximum spillway capacity $>$ 2000 cubic metres per second,
   d) especially difficult foundation problems were encountered, or
   e) the dam involved unusual design features.

A review of the types of instruments used by other organizations may also indicate the types of appropriate new instrumentation which could be installed in Ontario Hydro's dams.

Although the instrumentation of every dam is site specific, and a single rule establishing the number and type of instruments to be installed cannot be applied to every dam, certain general trends do exist for particular countries and utilities. In this report, topics such as general instrumentation philosophy, number and type of instruments, frequency and method of measurement, and record of performance are discussed and tabulated for several of the foremost dam building countries/utilities of the world.

The first category of "instrumentation philosophy" involves those people responsible for the safety and monitoring of dams and their general approach to instrumenting dams. This includes such things as the measured parameters which take highest priority and the degree of emphasis placed on past experience. The category of "instruments" includes details of the parameters monitored, and general trends in the type and number of instruments used. The third category of "measurement" involves the frequency and accuracy of measurement, and the degree of automation in data acquisition and transmission. The final category of "performance" involves the success of the instrumentation program, and whether a sufficient or excessive number of instruments has been installed, in the opinion of the dam engineer(s).

Each of these categories is considered in turn, for the following countries and utilities:

1. Norway
2. Switzerland
3. United States
4. Australia
5. Great Britain
6. France
7. Hydro Quebec
8. BC Hydro
9. Ontario Hydro

Where possible, case studies have been provided to supplement the tendencies in each country. A distinction has been made between the monitoring practices for concrete and embankment dams, where applicable. General trends are summarized and tabulated, and recommendations regarding Ontario Hydro's practices are provided.

2.0 NORWAY

2.1 Philosophy

Dams in Norway are owned and operated by either private, semiprivate, or national companies. However, the control of all water power resources is under complete state control through the Norwegian Water Resources and Electricity Board (NVE). A special department known as VVT, within the Water Resources Directorate of the NVE, is responsible for the supervision of dams. The Code of Practice for Dams requires that provisions be made for monitoring the performance of dams but, except for measurements of seepage and surface deformation, the Code does not specify what is to be monitored or for how long.

Most large Norwegian Dams are of the earth and rockfill type and are founded on high quality bedrock, with similar construction to many Ontario Hydro dams. Consistently similar construction materials and design have contributed to the "modest" instrumentation of Norwegian dams compared with the practices in many other countries. Extensive instrumentation is only installed if the dam design deviates significantly from existing types or if it is the first of a new class or type of dam, especially if many similar dams are anticipated to be built in the future/1/.

Generally, the routine process includes:

- measurements of seepage to evaluate the long-term performance of the structure,
- measurements of deformations of the dam by geodetic methods, and
- measurements of pore water pressure in the core material to verify that the embankment is being constructed at a safe rate.

2.2 Instruments

The principal factors in the selection of instruments are robustness and proven reliability over long periods of time. The majority of instruments are of the vibrating wire type and have been developed at the Norwegian Geotechnical Institute. To illustrate the scope of instrumentation activity, a list of the most extensively instrumented Norwegian embankment dams is presented in Table I/2/.

2.2.1 Surface Deformations

Horizontal and vertical movements of a network of reference monuments are determined by geodetic observations. Generally, these measurements are made by triangulation or with the use of electronic distance measuring (EDM) equipment/2/.

2.2.2 Internal Deformations

Horizontal displacements within the dam are usually measured with inclinometers in heavy duty steel tubular casing. Telescopic joints are usually placed at 3 m intervals and their positions are located with either mechanical pawls or magnetic probes. In dams with sloping cores, the casings are placed parallel to the core, generally at both the upstream and downstream sides. Horizontal casings are often installed perpendicular to the dam axis, between the core and dam surface, for measurements of displacements within rockfill shells. Extensometers are also commonly used to measure internal deformations. They are installed horizontally and aligned parallel to the dam crest, and are mounted between two anchor plates in the soil. Several 4 m to 12 m sections are often linked together to form continuous chains/2/.

2.2.3 Seepage

A barrier is usually constructed across the valley floor to form a permanent collection basin, which is divided into two parts where possible, to measure seepage from the left and right half of the dam separately. Seepage water is

run to a weir station usually located at the downstream toe. Flow rate is determined by use of a V-notch weir, a buoyancy force gauge, and a microprocessor based readout instrument/2/.

2.2.4 Pore Water Pressure

Both twin tube hydraulic piezometers and vibrating wire electrical piezometers are used in Norwegian dams. They are either built into the embankment material during construction or are placed in boreholes in the foundation material/2/.

2.2.5 Total Pressure

Instruments are sometimes installed for measuring soil stresses in the core and filter zones where tensile stresses are most likely to occur. Stress measurements are conducted primarily to study the conditions associated with differential settlements and the potential development of cracks in high dams with thin impervious cores. These measurements are not made routinely, but when included in a monitoring program, it is felt that a relatively large number of instruments must be installed if the program is to have any chance of success. Small diameter membrane-type pressure transducers, thin oil-filled hydraulic capsules connected to a pressure transducer, and oil-filled capsules connected to a hydraulic pressure sensing device have all been used to monitor internal stresses in Norwegian dams.

2.3 Measurement

On small projects with a limited number of instruments, data are often recorded manually with the aid of simple portable instruments. On large projects, and especially those in remote areas, data are recorded automatically by small microprocessor-based data loggers, on punched paper, magnetic tape, or by line printer. Measurements are usually continued throughout the first two or three cycles of filling and drawdown of the reservoir. Thereafter, their frequency is considerably decreased and usually only leakage and surface deformations are systematically monitored. Seepage data is recorded continuously on strip chart recorders and then transmitted to the nearest power station control room. In some parts of Norway, data are relayed to a control station which monitors the seepage for all dams in the area.

2.4 Performance

Information on the performance of Norwegian instrumentation systems is extremely limited, except for the Vatnedalsvatn Main Dam discussed in Section 2.5.

2.5 Case Studies

The following case study serves to illustrate the monitoring practices for an extensively instrumented Norwegian rockfill dam.

The Vatnedalsvatn Main Dam was the second to be built in a series of a new generation of relatively high Norwegian rockfill dams. It was therefore extensively instrumented in a manner similar to that used at the Svartevann Dam, the first of this new generation.

A summary of the instrumentation installed in the Vatnedalsvatn Main Dam is presented in Table II. A large number of survey monuments and a wide variety of internal displacement measuring devices are evident. The prevalence of vibrating wire type piezometers, total pressure cells, and extensometers is also illustrated.

A centralized, automated data acquisition system was installed in the instrument house at the downstream toe of the dam and was used to monitor virtually all of the electrical vibrating wire sensors. Details of the frequency of readings were unavailable for most of the instruments, and are thus not included in Table II.

Of the 111 electrical sensors, there has only been one instrument failure (1984) in the first year of operation. There have been very few problems associated with the sensors, and their performance appears to be excellent. This is due in part to overvoltage protection devices which have, without doubt, prevented several failures from electrical storms. Although the general performance of the instruments is excellent, the reliability of the data for some of the total stress measurements appears questionable. This may be due to change in orientation of the instruments after installation, the presence of large stones just below the prepared bed for the instrument, or differences in compaction of the backfill placed over the instruments relative to the surrounding soil/2/.

3.0 SWITZERLAND

3.1 Philosophy

The 182 dams in Switzerland are comprised of 127 concrete dams and 55 embankment dams. Only three embankment dams are of importance to the Swiss, due to their heights of 155 m, 120 m and 91 m. The other fill dams are all less than 45 m high and are mostly even less than 20 m high. It follows that concrete dams predominate, both in their importance and in proportion to the total number of dams. Of the 182 dams, 172 are used for the production of hydroelectric power. The water loads usually follow a seasonal cycle due to glacial runoff. Filling usually occurs in summer and emptying in winter, with water levels often changing 10's of meters due to the very steep sides and narrow nature of the reservoirs. The highest water levels are reached in autumn or early winter and the lowest in April or May.

Switzerland is a densely populated country in which the forces of nature play a predominant role in the monitoring of dams. The threat of such events as avalanches and earthquakes make dam owners and operators markedly safety conscious and highly aware of their responsibilities. These factors have also led to a relatively extensive level of instrumentation in Swiss dams.

The safety of Swiss dams is governed by the Federal Law Regarding Supervision of Hydraulic Structures. Federal supervision is justified by the fact that so many towns, buildings, roads, and railway lines lie close to rivers downstream

from dams, and are thus within the potential flooding zone of even small reservoirs. Dam Regulations call for a check of a dam's condition at least once a year by an experienced civil engineer/3/. Every Swiss dam is also under the supervision of a dam expert who follows its behaviour very closely and is required to conduct a major detailed inspection at least every five years/4/.

During the life of the dam, the most critical events are considered to be first filling, the possible occurrence of major earthquakes, and aging phenomena which increase after approximately 50 years. Thus, monitoring systems must be designed for a long life, or must be repaired or renewed periodically/4/.

3.2 Instruments

The instrumentation of a dam must include equipment designed to satisfy the following three requirements:

1. It must record the behaviour of the dam with simplicity and precision according to the loads (water load, pore pressures, temperature changes, etc).

2. It must be able to measure specific auxiliary parameters of special importance for the safety of a particular dam.

3. It must be designed to reference the whole of the dam/foundation system to a more distant zone which is uninfluenced by the loads acting on the dam.

The basic parameters measured to satisfy requirement #1 are:

- reservoir water level
- temperatures at selected points (concrete dams)
- uplift pressures/pore pressures (concrete/embankment dams)
- deformations
- seepage
- discharge of downstream springs

The auxiliary parameters often measured to satisfy requirement #2 are:for:

- internal deformations of the foundation
- turbidity of seepage water
- prestressed anchors.

A Geodetic measurement net is commonly used to satisfy requirement #3.

It should be noted that the diversity of conditions at various dam sites makes it impossible to standardize instrumentation for all dams. Despite this, several instrumentation practices have become the "norm" rather than the exception in Switzerland/3/.

3.2.1 Surface Deformations

Surface deformations are determined by geodetic measurements, which primarily serve to confirm the deformations determined by interior instruments such as pendulums. The geodetic network must extend beyond the zone of influence of the dam and the reservoir. Liaison between the interior and exterior systems can be achieved by using an optical plumbing shaft, or by connecting plumb lines and internal traverses of galleries to the geodetic network through openings in the downstream face of the dam, or by a combination of both these procedures. If an internal measuring instrument indicates abnormal dam behaviour, the geodesy is used to confirm and determine more precisely the zones of the dam or abutments which are affected. If no confirmation is obtained, it is likely that the internal measuring device is defective.

The preceding considerations show that geodetic measurements complete the internal monitoring scheme of the dam and its foundations/3/.

3.2.2 Internal Deformations

In most cases, adequate monitoring of the internal deformations of concrete dams is assured exclusively by plumb-lines/pendulums. Installation in existing concrete dams can often lead to excessive investments. Thus, when the costs become disproportionate to the value of the data obtained, as for many smaller dams, geodetic surveys of surface monuments must suffice. In straight gravity and earthfill dams, wire alignment is often used, wherein the wire is stretched from one side of the valley to the other and is located in the control gallery or crest parapet. Optical alignment is applicable to all types of dams and is especially useful where it is not possible to install pendulum or wire alignment equipment/4/. When the deformation curve of a dam must be determined with precision, after some abnormal behaviour for example, it is not uncommon to use a sliding micrometer. Foundation deformations are primarily monitored with inverted plumb-lines/pendulums, when justified financially, and sometimes with rockmeters (extensometers)/3/.

3.2.3 Reservoir Water Level

Rittmeyer type pressure balances are virtually the only type used at present, to provide continuous, automatic, and safe measurement of the reservoir water level for every Swiss dam/3/. The pressure balance is connected to the reservoir water level so that changes in water level cause changes in gauge pressure.

3.2.4 Seepage

Systematic measurement of seepage through a dam is usually only possible if a base gallery (inspection tunnel) and a drainage system with a collector exist. However, the more common practice, especially for small dams, is to restrict measurement to the discharge of any downstream springs. The measurement is usually volumetric and often involves V-notch weirs and automated equipment.

Discharge measurements are sometimes complemented by chemical analyses. Three portable instruments are currently in use, to permit the on site determination of pH, conductivity, and dissolved oxygen content. Turbidity is usually evaluated visually, but instruments have been installed to provide continuous monitoring/3/.

3.2.5 Pore Pressure (Embankment Dams)

In embankment dams, pore pressure measurements are primarily used to determine the location of the seepage line. For most existing dams, which appear to be behaving normally, measurements are usually restricted to open standpipe piezometers. Where pore pressures are needed at several depths, either pneumatic or electric piezometers are installed/3/.

3.2.6 Uplift Pressure (Concrete Dams)

The measurement of uplift pressure is usually conducted using lined boreholes fitted with manometers. In some instances, the reservoir and manometers have been linked with pipes to allow periodic checking of the manometers under known hydrostatic pressure. Where uplift pressures must be determined at different depths, Gloetzl type pneumatic piezometer cells are usually used, allowing readings to be made in a central measurement chamber/3/.

3.2.7 Temperatures - (Concrete Dams)

The failure of old instruments embedded in the concrete, and the difficulties associated with interchangeability, have led to the use of simple thermometers, which are inserted and withdrawn in open boreholes for every measurement/3/.

3.3 Measurement

The recommended accuracies for several different types of instruments are summarized in Table III. It may be seen that the monitoring of displacements for concrete dams consistently requires a higher degree of precision than the same measurements for embankment dams (ie 0.2 mm for concrete versus 1 mm for embankment). The precision for certain parameters such as seepage and total pressure is established as a percentage of some maximum value, and is thus variable for different locations within the dam.

Automatic data acquisition systems are not considered imperative despite their benefits. These benefits include the possibilities of continuous recording, a consistent measurement technique, and an ability to monitor under adverse weather conditions, during which a dam may be rendered inaccessible. If the frequency of visual inspections and manual measurements is appropriate, the behaviour of the dam can be checked satisfactorily and any deviations detected sufficiently early. Also, a significant majority of all dam failures have been first detected by visual inspection and instrumentation has been used to "pinpoint" the location and cause of the problem.

Automatic recording is usually restricted to those parameters which are most important for analyzing the behaviour of the dam. These often include reservoir water level, possibly one or more measurements of typical temperatures, uplift pressure values (if needed), characteristic deformations, seepage and, for embankment dams, pore pressures.

The number of automatic gauges and instruments should be sufficient to ensure that if one of them breaks or malfunctions, continuity of measurement is maintained. The signals are generally transmitted digitally, particularly where data is to be analyzed by computer. When long distance data transmission is intended, the system must be protected against all external influences, especially stray currents from lightning.

The installation of automatic monitoring equipment should be justified on the basis of the assistance provided to dam wardens, so that their effectiveness in critical observation of the dam, in precise measurements, and in regular interpretation of the results will be increased. The automated electronic equipment should complement the existing monitoring equipment rather than replace it, thus allowing verification of the results by manual measurement.

3.4 Performance

In the majority of Swiss dams, the performance of the instruments installed has been satisfactory to excellent. Malfunctioning and/or broken instruments have been minimal to date, and the causes of the few problems have, in most cases, been discovered and corrected/4/.

3.5 Case Studies

The instrumentation and performance of four different types of Swiss dams have been summarized in Table IV. It may be seen that the concrete dams built in the 1960's were instrumented with emphasis placed on survey monuments, pendulums, inclinometers, and uplift pressuremeters. The embankment dam was similarly instrumented with emphasis on survey monuments, extensometers, piezometers, and total stress meters. For the Spitallam dam built in 1932, importance seems to have been placed on seepage and pore pressures, with unknown amounts of instrumentation for the measurement of deformations. The performance of all four monitoring systems has been satisfactory to excellent/3/.

4.0 UNITED STATES

4.1 Philosophy

The most prominent organizations for evaluating the safety of dams in the United States are the Bureau of Reclamation and the Army Corps of Engineers. Great emphasis is placed on the inseparable nature of engineering judgement and appropriate instrumentation. The method described by Terzaghi, and endorsed by Peck and Casagrande, places visual observation and evaluation of site conditions by experienced engineers as the primary need, with instrumentation of perceived problem areas being secondary. The history of major dam failures in the United States has seemed to demonstrate that the

instrumentation provided in each case was not selected, installed, observed, or evaluated in a sufficiently timely manner to permit adequate forecast of, and offsetting measures against, inadequate safety/5/.

Many of the problems associated with the development of an instrumentation program may be avoided if they are given due consideration before dam construction begins. A clear, essential, and achievable objective for the program should be defined. The minimum number and type of instruments needed to obtain the "necessary" data should be determined, and the need for automatic data acquisition and transmission should be defined. The cost of installation, maintenance, monitoring, and data evaluation must also be considered since these costs may supersede the aforementioned factors/5/.

4.2 Instruments

In 1982 the US Army Corps of Engineers established a classification system for dams, based upon potential for loss of life and property damage. It follows that the amount of instrumentation for any particular dam is, to a large extent, based upon its hazard classification. However, regardless of the risk involved, the parameters which take highest priority in American dams are seepage and surface displacements. Ideally, instruments used in a given situation should have the following characteristics:

- sufficient accuracy
- long-term reliability
- simplicity
- low maintenance requirements
- compatibility with construction techniques
- low cost.

Realistically, the optimal balance of these often conflicting characteristics is sought/6/. Where measurements are essential to the safe functioning of a dam, two different types of instruments should be installed for a given observation/7/.

4.2.1 Surface Deformations

Typical triangulation and trilateration surveys are conducted by geodetic methods on monuments placed on the crest and downstream faces of dams. Both settlements and horizontal displacements are usually measured. The Bureau of Reclamation typically requires an accuracy of 1 part in 10,000 or 0.01 ft (ie second order/Class II survey) for embankment dams, and high order precision surveys for concrete dams/6/. A wide variety of strain meters, crack and joint measuring devices, and plumbing and tilt measuring instruments have been used successfully to monitor the behaviour of concrete structures during external loading/7/. The number of instruments installed in any dam depends on the size and type of dam, the structural geology of the foundation, and the potential for displacement.

4.2.2 Internal Deformations

Typical instruments used to determine settlements of embankment dams include foundation baseplates and pneumatic and vibrating wire settlement sensors. Fixed and normal inclinometers are also used to measure settlements and

relative lateral movements. Inclinometers are expensive to install and to monitor, and therefore their use is usually limited to more important embankment structures and to those with obvious deficiencies. Multipoint extensometers of the rod, wire, and tape types are used by the USBR to measure axial displacements. The extensometers are normally installed in uncased holes and are suitable for measurements in any orientation. Shear strips have also been used to measure differential movements in rock, soil, and concrete. The strips may be hundreds of feet in length, grouted into boreholes, or attached to a rock or concrete surface/6/.

4.2.3 Seepage

Seepage and leakage through the dam, the abutments, or the foundation is usually measured with a particular type of sharp-crested weir. The 90^{0} V-notch weir is particularly suited for small flows, but standard compacted and standard suppressed rectangular weirs are also extensively used. When the elimination of sediment deposition within the flow measuring system is needed, and a wide range of flows with a relatively small head loss must be measured, a Parshall flume is often installed. Other devices commonly used include velocity meters and calibrated containers for low flow velocities. Thermotic surveys have also proved particularly useful in identifying zones of high permeability and flow concentrations within fractured rock and surficial deposits/6/, and self-potential surveys have been used to monitor seepage loss from reservoirs.

4.2.4 Pore Pressure

The USBR has made an extensive contribution to the development of various types of pore water pressure measuring devices (piezometers). Approximately 2800 hydraulic twin-tube piezometers were installed in USBR dams between 1939 and 1981, but many of these have been abandoned because of breakage or plugging problems/6/. Therefore, the systems now being installed in USBR dams are of the pneumatic or vibrating wire type. These are installed both in foundation and embankment materials, to measure uplift pressure and flow patterns respectively. Their primary advantage is that they may be used where construction practices could damage other types of instrumentation such as standpipes. Porous and slotted-tube piezometers and observation wells are often installed after the completion of construction. The advantages and limitations of several piezometer types are indicated in Table V/6/.

4.2.5 Total Pressure

Pneumatic and vibrating wire total pressure cells are used to monitor the static total pressure in dams. Piezometers must be located near the cells so that the water portion may be subtracted from the total pressure to determine the effective earth pressure. The cells are often installed at material interfaces to determine the contact pressure/6/.

4.2.6 Seismicity

The primary instruments used by the USBR to measure significant vibrations are "strong-motion earthquake instruments". Nearly all these instruments use servo-accelerometers to measure motion in a single horizontal, vertical, or transverse plane. Bolt and Hudson recommend that seismographs be placed

monitor seismicity induced by impoundment. The instruments are best located on bedrock outcrops and should be remote from construction activities, quarries, and streams/8/. A great deal of emphasis is placed on the historical seismic data of a particular area. This data is used in the design of new dams and in the modification of existing dams to make them withstand earthquake loadings appropriate to their locations.

4.2.7 Water Quality

Water quality testing is commonly performed to detect the possible solutioning of rock or chemically bound aggregated soil materials, the possible erosion of soil particles, or the development of new seepage paths. Commonly performed field tests include pH, temperature, conductivity or specific conductance, and occasionally, turbidity. Laboratory tests often include pH, conductivity or specific conductance, total dissolved solids, total suspended solids, total cations and anions, and commonly found "minerals" such as: calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulphate and chloride.

4.3 Measurement

Manual recording seems to remain the predominant method of gathering data. Full automation has been accomplished at only 5 USBR concrete dams and 2 USBR embankment dams. The instrumentation systems involve automatic reading instruments and either telephone or satellite telemetry. The transmission of data has progressed from the mailing of field data forms, to the use of portable teletranslational computers. Instrument readings are entered and stored in the portable computer, and the data is then transferred to a separate terminal for long distance transmission. All computations are performed automatically, increasing the speed and accuracy of data processing.

Investigations are currently underway to evaluate the effectiveness of computers equipped with artificial intelligence to monitor and assess instrumentation data as it is recorded. When threshold values are exceeded or abnormal dam behaviour is detected, dam personnel are automatically contacted by the computer. Increasing emphasis is thus being placed on the value of automation, but the USBR will proceed cautiously and explore the feasibility of instrumentation automation on a case-by-case basis/9/.

The frequency of measurement depends not only on the purpose of the instrument being monitored, but on the status of the dam at the time of measurement. Tables VI and VII indicate typical reading frequencies for several instruments at various stages in the life of an embankment dam and concrete dam respectively/6,8/. The inspection program usually involves three grades: technical inspections, maintenance inspections, and informal observations.

Technical inspections include detailed visual examinations of the dam, the spillway, and important machinery, and a review of existing records, reports, and photographs. These inspections are to be systematic and comprehensive and are to be conducted by an experienced civil engineer. A dam which has not been properly inspected by experts for many years or a new or reconstructed dam should be inspected semiannually initially to obtain baseline data and general familiarity.

As inspectors become more familiar with the dam, the frequency of inspections may be reduced but should not be extended beyond once in 5 years even under the best of dam conditions. Special technical inspections should also be conducted after a major problem or event such as earthquake, flood, vandalism, or sabotage.

Formal maintenance inspections should be conducted on a semiannual to annual basis to monitor the behaviour and condition of the structure and all operating equipment. The inspection should be performed by an engineer or experienced supervisor of dam operations, and should include examination of all monitoring equipment and instruments. Changes in physical conditions such as erosion, corrosion, subsidence, and blockages of drains should be noted. All gates and emergency power sources should also be inspected and operated if feasible.

Informal observations may be made by dam operators and maintenance personnel in the course of their routine operational activities. These individuals should be encouraged to report unusual events or strange conditions to provide another means of surveillance/8/.

4.4 Performance

Data on the success of various instrumentation programs or on the performance of individual instruments was unavailable.

4.5 Case Studies

Anomalous performance of the Fontenelle Embankment Dam prompted the US Bureau of Reclamation to limit reservoir operations and establish an extensive and unique instrumentation and investigation program to monitor possible recurring foundation problems.

The Fontenelle Dam is a 42 m high zoned earthfill structure completed by the USBR in 1964. The safety of the dam was first threatened during the initial filling in September 1965 when a section of the embankment near the right abutment collapsed due to seepage and piping. Emergency drawdown of the reservoir prevented breaching. The core material had been placed directly against the rock abutment and foundation with no intervening transition layer. Seepage water passed around the grout curtain through a pervious bedding plane. This seepage, under significant hydraulic pressure, began erosion of embankment material along the embankment-foundation contact. This erosion proceeded upstream and was accompanied by embankment caving and piping. Between 1965 and 1966 the troublesome section was removed and rebuilt and the grout curtain reinforced and extended further into both abutments.

Prior to the emergency, instrumentation consisted of:

50 embankment measuring points,
139 structural measuring points, and
3 seepage monitoring points.

Following the embankment repair a total of 27 observation wells were installed in the abutments and downstream of the dam. Monitoring of these wells indicated encouraging performance of the dam, and as a result, refilling commenced in the spring of 1968. Seepage flows remained stable until June 1982.

In 1982, large local settlements and increases in seepage were detected. An electrical self potential (SP) survey was conducted to delineate seepage flow paths in more detail than existing boreholes and surface observations would allow. Four major SP anomalies were detected. Water quality tests were also conducted and indicated significant quantities of soluble foundation material. However, the inability to measure the rate and location of solutioning with precision, prevented the formulation of conclusions regarding the effects of solutioning on the dam structure.

Conventional methods were thus deemed inadequate, and a temporary thermotic monitoring system was implemented. The system consisted of 40 thermistor probes calibrated to 0.01^{o}C installed in 3 m deep holes in a line along the downstream toe of the dam. The thermistors qualitatively confirmed the existence of channelized flow paths in the left-most portion of the foundation. Geologic investigations, including cone penetration tests, trenches, test pits, dye and pump-out tests, indicated a high potential for embankment piping. The frequency of monitoring was also increased to the values indicated in Table VIII. Automation of some key thermistors and other instruments was planned to facilitate analysis of the large volumes of data produced.

The combination of conventional and unconventional techniques was successful in determining the source and cause of increased settlement and seepage rates. The poor installation of several piezometers made the interpretation of quantity and significance of suspended solids difficult. Cone penetrometer tests proved particularly useful in identifying numerous soft and potentially unstable zones within the embankment.

5.0 AUSTRALIA

Sections 5.1 to 5.3 inclusive have been taken from "Guidelines for Dam Instrumentation and Monitoring Systems", ANCOLD 1983/11/.

5.1 Philosophy

The primary objectives of instrumentation systems in Australia are:

- to confirm design assumptions and predictions of performance during construction of the dam and first filling of the reservoir,
- to provide early warning of the development of unsafe trends in behaviour of the dam and associated structures during the general operation phase,
- to provide data on the behaviour of dams which do not satisfy modern criteria and warrant continuous monitoring as a guide to the urgency for the introduction of remedial measures.

- to provide data on structural and seepage behaviour in response to remedial/stabilizing works to ensure that the additional loading will not adversely affect the safety of the dam.

The complexity and extent of instrumentation and monitoring is dependent not only on the above factors, but also on the "hazard rating" which is based on the US Corps of Engineers Criteria. The number and distribution of instruments depend on such factors as the type of dam and foundations, site topography, and regional seismicity, and for a new dam, are oriented primarily to problems envisaged at the design stage. For large dams, numerical analysis plays a large role in the disposition of instrumentation systems.

Besides a hazard classification, a size classification system has been established as follows:

Small - between 10 m - 15 m in height with a storage capacity of more than 20,000 m^3 or

- between 5 m - 10 m in height with a capacity of 50,000 m^3 or more.

Medium - between 15 m - 100 m in height with a storage capacity greater than 20,000 m^3

Major - greater than 100 m in height with a storage capacity greater than 20,000 m^3.

Further distinction is drawn between concrete, fill, and deck (impervious upstream face) type dams.

Seepage and pore pressure measurements are regarded as the first and second most significant factors respectively, in assessing the behaviour of fill dams. In concrete dams, the measurement of displacements seems to play a predominant role.

5.2 Instruments

5.2.1 Concrete Dams

5.2.1.1 Surface Deformations

Surface displacements are monitored by a precise survey system generally based on a triangulation and/or trilateration network which is established with a high degree of accuracy. A subsidiary survey control system for measurement of the deformation is fixed from the basic control system as precisely as the equipment and topography will allow. Pillars should be incorporated in the control network for the construction of the dam, to allow any necessary alterations to be implemented if periodic movements or any anomalies are detected. The pillars should be located in consultation with the design engineer, geologist, and surveyor. The basic control network will depend on the topography, but, if possible, should consist of a well formed, braced quadrilateral.

It is recommended that angles be read on eight zeroes with a range not exceeding three seconds, and that misclosures should average one second with a maximum of three seconds. Similar accuracies should be aimed at for the subsidiary control network. If subsidences are required, they are usually observed to +/- 1 mm, and differences on each set up should not exceed 0.4 mm.

It is essential to obtain a full set of readings immediately after completion of construction and before filling of the reservoir commences. Surveys are often conducted at predetermined water levels after construction.
In concrete dams with contraction joint openings or cracks, joint meters are often installed to measure deformations resulting from the structural readjustment of the dam. In its simplest form, the instrumentation may consist of a dial gauge between pins on either side of the joint or crack. Where continuous and accurate monitoring is necessary, commercially produced electrical joint meters are usually installed. Typical accuracy is +/- 8 x 10^{-6} strain units or +/- 0.1% of the range of movement.

5.2.1.2 Internal Deformations

Normal and inverted pendulums provide vertical reference lines through an anchorage point, to which the deflection of a dam wall may be related. Deformation readings may be obtained using a hand micrometer, Vernier microscope, or optical coordinometer with respective accuracies of +/- 0.1 mm, +/- 0.01 mm, and +/- 0.01 mm. When highly accurate measurements of vertical lines are necessary, optical plummets are used. Measurements of rotation or tilt are done with inclinometers and/or tiltmeters. Direct reading and portable tiltmeters are typically installed on gallery walls or external faces. Remote reading devices are usually permanent installations with electrical sensors.

Strain measurements are not normally made on concrete gravity dams except where unusual problems exist. However, in arch dams, the calculation of stresses from strain measurements enables a comparison to be made between design and in-service values allowing identification of any problem areas. The most valuable information is gained if the initial filling is rapid and creep effects are negligible. During subsequent operation, the absolute values of strain may be in question, but the meters will continue to indicate any significant changes in stress patterns. Vibrating wire strain gauges have not been used in arch dams in Australia for field strain measurement. This is possibly due to the greater ease of reading the resistance/Carlson type of meter and the fact that temperature is obtained from Carlson meters without the need for additional thermometers.

5.2.1.3 Seepage

Seepage measurement for concrete dams is used primarily as a guide to determining the continuing effectiveness of the grout curtain and drainage systems. Measurements are usually taken at intervals along an internal drainage or inspection gallery which conventionally includes a drain/gutter in the floor. If the gallery does not extend into the abutments, seepage measurements are taken at points along the downstream toe, as in the case of smaller dams without galleries. Seepage weirs of the V-notch or pipe type (see Section 5.2.2.3 for details) may be installed downstream, but outlet

works releases may reduce their usefulness. Further details of weir installations will be given in the section on fill dams since the considerations are applicable to both concrete and fill dams.

5.2.1.4 Uplift Pressures

Seepage pressure measurement systems for concrete dams normally involve measurement of pressures at the dam/foundation interface and within the foundations. In older dams, measurements are made "down the hole", utilizing holes drilled from the drainage gallery or downstream toe. In new dams, pore pressure measuring cells are installed during construction at locations similar to those for older dams.

Where the structural behaviour of a dam is to be monitored by deformation, tilt, and temperature measurements, a seepage/uplift pressure measuring system in the foundations is necessary for the interpretation of the dam's behaviour. It also serves to monitor the long term effectiveness of grouting and drainage provisions in reducing seepage pressures within the foundation. On stratified foundations, where drainage cutoffs are of critical importance to stability, the measurement of seepage pressures within the foundation requires additional emphasis.

In existing dams, uplift pressures are determined using drill hole installations, such as hydraulic, electrical, or pneumatic piezometers, or back pressure gauges with a seal at the top of the hole. In new dams, pore pressure cells of similar types are installed at discrete locations within the foundation or at the foundation/concrete interface. For concrete dams, no emphasis is placed on negative pore pressures and filter discs can accordingly be relatively coarse.

5.2.1.5 Total Stress

Compressive stresses within dam concrete have been monitored with Carlson type stress meters. Documentation of results is very limited but the quoted accuracy of the meters is +/- 5%. The repeatability of stress variation with reservoir water level and time is taken as an indicator of the continuing acceptable structural performance of the dam.

5.2.1.6 Temperature

Temperature measurements within the concrete are sometimes carried out during construction as a control on placement rates which are primarily dictated by the heat of hydration. Temperature data may also provide a guide to the optimal time for contraction joint grouting. In gravity dams, measurements are normally discontinued following construction. However, in arch dams, the measurements are continued in the service phase of the dam, to provide an appraisal of the influence of temperature on deformations as compared with design predictions. Where general temperatures are required, mercury thermometer probes are inserted into pipes in the dam walls or in galleries. Where a rigorous study of deformation is warranted, permanent temperature meters may be installed within the concrete.

5.2.2 Fill Dams

5.2.2.1 Surface Deformations

Survey networks are established and monitored as in the case of concrete dams. Datum benchmarks should be connected to the State datum by precise levelling. The primary difference between geodetic networks for embankment and concrete dams lies in the types of survey targets and the methods of installation.

5.2.2.2 Internal Deformations

Many types of instruments are used to measure horizontal and vertical displacements within fill dams.

Vertical movements (settlements) are often monitored by cross-arm type instruments in earthfill dams, and by hydrostatic settlement gauges in rockfill dams. These devices provide a means of determining volume changes, foundation settlements, and the behaviour of rockfill. Both the mechanical USBR type and the electrical SMEC (Snowy Mountain Engineering Corporation) type of cross-arm gauge are used within Australian fill dams. Settlements in rockfill "zones" are also often measured with hydrostatic settlement cells. These instruments are analogous to a dual system U-tube manometer with one set of free surfaces in the gauge embedded in the fill and the other set in readable standpipes located on the downstream face or abutment.

Vertical movements can also be measured with comparable accuracy by use of the Idel system. The Idel sonde experiences a change in frequency when it encounters metal plates placed at regular intervals along a telescoping plastic tube. The system is installed as construction of the embankment proceeds, and in the case of vertical tubes, can be used for measurements before construction of the dam is complete. Manufacturers claim an accuracy of +/- 1 mm but practical experience has quoted best results of +/- 15 mm. A very similar system utilizes ring magnets and a magnetic field sensing device which slides along the plastic tubing. Reported accuracy in this case is +/- 1 mm.

Horizontal movements are measured with long wire extensometers or the Idel system. The former are installed horizontally and normal to the dam axis, and indicate the position of cross-arms in relation to a fixed reference point, usually on the downstream slope. The extensometer system consists of telescoping segments of 75 mm and 100 mm diameter steel pipes, measuring wires connecting to cross-arm units, a pulley assembly with tensioning weights, and a measuring scale. The accuracy of this equipment is assessed as +/- 1.5 mm. The Idel system used for horizontal measurement is virtually identical to that used for vertical measurements. However, the quoted accuracy is +/- 1.5 mm. The actual reading procedure is more complicated than the long wire extensometer, and problems have been encountered due to differential settlement and jamming of the sonde.

Grooved and smooth pipe inclinometers are also used to measure horizontal and vertical movements. The grooved pipe inclinometer is commonly used in the upstream or downstream faces of the core to provide data on horizontal displacements during construction and operation. The smooth pipe inclinometer has been used to measure the movements of the concrete face of a decked

rockfill dam, and in a modified form will survey vertical pipes set in fill. The accuracy of the smooth pipe system is reported to be +/- 3 mm at the midpoint of a 150 m pipe.

Crest deformations are commonly measured by resistance type strain gauges. The SMEC type consists of several (ie 40) separate extensometers each with a gauge length of 3 m between cross-arms. The QWRC (Queensland Water Resources Commission) developed a 32 m long gauge comprising eight 4 m long units installed 3 m below the dam crest. In decked rockfill dams, strains below the upstream face are often monitored by 12 m long Carlson type strain gauges. A galvanized steel rod is encased in sliding steel pipes and measurements of 0.1 mm are possible. The range of motion is usually 8 mm in compression and 32 mm in tension. Strains on the actual face are measured by 250 mm strain meters.

5.2.2.3 Seepage

Where seepage flow is significant, a V-notch weir or similar system is usually installed. If debris tends to get caught in the notch, a Pipe-T weir can be used (see Figure 1). When flows are less than 0.1 litres/second, timed discharge into a hand held container usually suffices. Flows that are just evident are inspected visually and an appraisal made by the observer. Inexplicable increases in flow or signs of turbidity should be investigated by appropriate engineering personnel. It should be noted that rainfall may have significant effects on flow rates and seepage colour, and either a delay in seepage measurements or a correlation between seepage flow and rainfall may be necessary.

5.2.2.4 Pore Pressure

The importance of pore pressure measurements ranks second only to seepage measurements in earthfill dams. The primary requirements of any piezometer are:

a) accuracy and the ability to measure negative pore pressures if their existence is possible,

b) a lack of effect on the flow regime in which it is installed, and

c) an adequate response time to any changes in pressure.

A wide variety of piezometers have been installed in Australian fill dams. These include open standpipe, hydraulic, pneumatic, vibrating wire, and electrical resistance piezometers.

A strong preference for any particular type is not evident. Each type has certain disadvantages associated with it such as damage and inaccuracy due to differential earth settlements, trapped air, or stray electrical currents.

5.2.2.5 Total Stress

In fill dams, total stresses are used to verify mathematical models, to indicate possible changes in material strength, and to determine the risk of hydraulic fracture. The two types of pressure cells in common use are the diaphragm cell and the hydraulic pad. In the diaphragm cell, the deflection

of the diaphragm is measured by electrical resistance strain gauges, by strain gauged transducers, or by vibrating wire frequencies. Hydraulic cells can be divided into two groups. The first is an oil-filled large diameter flat jack connected by a length of tube to a vibrating wire or pneumatic transducer. The second type of hydraulic cell is one in which the transducer element is integral (ie the diaphragm is internal). Experienced crews are essential in the installation of all total stress measurement devices.

5.2.3 Concrete and Fill Dams

5.2.3.1 Seismicity

For major dams where storage induced seismicity may occur and for dams in seismically active regions, a seismographic net and strong motion instrumentation should be considered. Monitoring of seismic events in conjunction with storage impoundment should be integrated into a regional net to provide a probabilistic appreciation of future seismic loading. Sensitive seismographs should be placed on basement rock outcrops, away from such things as construction, quarries, haul roads, large spillways, and large trees. Interstation distances should be between 5 and 30 km. Seismometers and strong motion accelerographs are also commonly installed, the latter usually having a threshold of 0.01 g.

5.2.3.2 Chemical and Biological Analysis of Seepage Water

A comparison of the chemical analyses of reservoir and seepage waters may be used as a guide to the location of deteriorating concrete and grout curtains or foundation materials. Biological analysis can often provide an indication of seepage course by a comparison of phytoplankton types in seepage water and ground water or storage water. The amount of algae in seepage water may indicate filtering if a low concentration is present, or the presence of fissures and cracks if a high concentration is present. The age of seepage water may also be determined by tritium analysis.

5.3 Measurement

Visual inspections are carried out by technical staff at regular intervals with emphasis on critical areas of dam behaviour such as cracking, sink holes, settlement, discolouration of seepage, and increased flow. Checklists must be completed, and if the change in any parameter exceeds the threshold value, it must be reported to engineering personnel. Inspections by engineers familiar with the design criteria and with previous records of inspections, should be conducted after one, two, and five years following first filling. Thereafter, if the dam has established a stable pattern of behaviour, inspections should be made by the engineer(s) at intervals not exceeding five years. More frequent inspections may be dictated after seismic events or if the dam exhibits unstable behaviour. Tables IX, X, and XI indicate the recommended frequency of instrumentation monitoring for various classes of fill, deck, and concrete dams respectively. Table XII indicates general trends in monitoring frequencies during construction, first filling, and routine operation.

The instruments which have been found to be particularly suited to automatic data acquisition and transmission include: foundation uplift piezometers, clay core piezometers, rock compression meters in the foundation, thermometers, accelerographs, seepage measuring devices, and reservoir water level devices.

5.4 Performance and Case Studies

The significant program of instrumentation at the Pieman River Power Development in Tasmania, has provided reliable data on five concrete faced rockfill dams. The program focused primarily on the measurement of deflection and deformation of the reinforced concrete membranes due to reservoir water loading. In addition, measurements were made of leakage, rockfill settlement, and deflection of dam crest and faces. In some instances, measurements were made of piezometric pressure, rockfill pressure, and displacement. Internal and external measurements of settlement and deformation have provided a good assessment of the overall behaviour of these dams. Details of the dams and numbers of instruments are given in Table XIII/12/. It may be seen that the most extensive areas of instrumentation are for the measurement of settlements, surface displacements, and seepage.

6.0 GREAT BRITAIN

6.1 Philosophy

The majority of dams in the United Kingdom are of the puddle clay core embankment type with ages in excess of 30 years, approximately 50 per cent being built before the year 1900. Some of the more recent dams have asphaltic concrete or rolled clay as the impervious element of the core and have reached heights up to 90 metres.

Reservoir legislation in Great Britain has been concerned essentially with imposing a system of safety checks on reservoir construction and operation. Two Acts of Parliament were passed for this purpose; the Reservoir (Safety Provisions) Act of 1930, and the Reservoir Act of 1975. The former required "undertakers" to keep records of:

a) water levels and depth of water, including the flow of water over the waste weir or overflow;
b) leakages, settlements of walls and other works, and repairs;
c) such other matters as may be prescribed.

Undertakers were defined as "persons for the time being carrying on any undertaking comprising or intended to comprise a reservoir, or when a reservoir is not used or intended to be used for the purpose of any undertaking, the owners or lessees thereof.

The 1975 Act went beyond the 1930 Act in a number of important ways.

(a) Enforcement authorities are given explicit duties. They are required to keep registers of all reservoirs (> 25,000 cubic metres capacity) and to demand full documentation from undertakers and engineers. They are also empowered, in certain circumstances, to carry out remedial work and recoup the costs from the undertakers.

(b) The statutory inspections are to be carried out by an independent panel engineer, who is not in the employment of the undertakers and was not the engineer responsible for the construction of the reservoir.

(c) The undertakers are required to appoint a named supervising engineer to keep the reservoir under continual supervision between inspections.

(d) Non-compliance with the Act's safety provisions is made a criminal offence.

(e) The period of appointment of panel engineers is limited to five years. An engineer can be reappointed for further terms.

(f) Procedures for the abandonment of a reservoir are prescribed.

Two features are of particular note in legislation under both the 1930 and 1975 Acts:

(a) Only engineers who are members of a specially constituted panel of civil engineers set up by the Secretary of State for the Environment can be appointed to inspect and prepare the reports on dam safety required by the Act.

(b) If damage or injury is caused by the escape of water from a reservoir, compliance with the requirements of the Act does not exonerate the undertaker from liability/13/.

A great deal of emphasis is placed on the information that can be gained from visual inspections/14/. Localized settlements, damp patches, unexpected deformation, and turbid seepage may all be signs of deterioration within the dam and further investigations may be warranted. These investigations have, to some extent, been conducted using various types of instrumentation, both within the dam and on its surface. Investigations have also been conducted using in situ tests/13/.

Although external measurements of crest settlement and seepage flow remain the basics of monitoring programs, the main thrust of current research by the Building Research Establishment (BRE) is concerned with direct means of internal assessment. Whereas external assessment may provide evidence of deterioration, the origin and nature of this deterioration can usually only be obtained by direct internal investigation. Several of the instruments used for these internal investigations are outlined in the following section/13/.

6.2 Instruments

6.2.1 Surface Deformations

External measurements of dam movements are monitored using 3 dimensional trilateration, 2 dimensional trilateration and levelling, or 3 dimensional triangulation surveys.

6.2.2 Internal Deformations

Horizontal movements are monitored with inverted pendulums, rod and cable gauges, or large numbers of horizontal plate gauges at discrete points. Chains of electrical strain gauges, each over 2 to 5 m in length, are also used to measure horizontal strains parallel to the dam axis.

6.2.3 Settlement

Settlements are often measured with water level overflow gauges in the upstream portion of fill in embankment dams/16/. They have also been measured by precise levelling of stations on the dam crest, by USBR crossarm settlement gauges, or by torpedo type deflection indicators/15/. Movements caused by the emptying and filling of the reservoir should be considered in these analyses/14/.

6.2.4 Seepage

Seepage is commonly measured with 90^{0} V notch weirs/15/.

6.2.5 Pore Pressure

The standpipe piezometer remains a popular instrument for measuring pore pressures because of its simplicity and reliability. It can also be used for permeability and critical pressure tests, but when used in soils of low permeability, the long response time is its main disadvantage. Pneumatic piezometers have a short response time but have been found to be less reliable than the standpipe piezometers and cannot be used for permeability and critical pressure tests. Hydraulic and electric piezometers have also been used, the former being most popular, because of poor performance of the electric piezometer in partially saturated soils/15/.

6.2.6 Total Pressure

The push-in pressure cell developed by the BRE is commonly used for the measurement of total stress in clay cores and is usually pushed into the clay at the bottom of a borehole. The instrument may incorporate a pneumatic piezometer, making it possible to determine effective and total stresses. Since the action of pushing the cell into the clay induces pressures, two to three weeks may be necessary before the excess pressures have dissipated and an assessment of lateral pressure can be made. Lateral stresses in the upstream-downstream direction are usually measured.

Total stress is also measured using the critical pressure test by increasing the level of water in a standpipe piezometer until a hydraulic fracture occurs. Following hydraulic fracture of the clay, the pressure is allowed to decrease as water escapes from the tip. The critical pressure is defined as the pressure at which the flow rate decreases to a value compatible with the permeability of the surrounding clay. The critical pressure is equal to the minimum principal stress but the direction of the principal stress remains unknown/13/.

Total pressure cells of the Gloetzl type have also measured total stress with some success/15/.

6.3 Measurement

No documentation was found regarding the monitoring frequency of various instruments or the degree of automatic data acquisition.

6.4 Performance

Some of the difficulties associated with different instruments installed in Keilder dam are outlined in the "Remarks" column of Table XIV/17/. Details of the adequacy of monitoring systems in general were unavailable.

7.0 FRANCE

7.1 Philosophy

The main purposes of dam monitoring in France are i) to check dam safety and detect any anomalies requiring action, in good time, and ii) to check the design criteria and assumptions by comparing actual and predicted performance. According to Salembier et al, instrumentation systems may be categorized as follows, based on their adequacy or inadequacy/18/.

- The instrumentation system may become more than ample over the years.
- There may be a need to adapt the system to actual operating conditions, or to improve or supplement it.
- The instrumentation system may be non-existent.

Electricite de France (EDF) engineers place more confidence in the frequent, careful, and prompt examination of records from a small number of instruments, than in the uncertain task of screening a large mass of data which tends to obscure the useful information. Thus, in particular instances where the system is excessively comprehensive, certain instruments may be read less frequently or may be completely abandoned, to increase the efficiency of the monitoring system.

Through technological advances, the improvement and modification of existing instruments is made possible. The addition of automatic data acquisition systems, computer analysis, improvement in existing instruments, and the development of new instruments have all led to the "progress" of dam monitoring.

Dams liable to affect the public must be inspected and monitored according to French law. Regulations stipulate the type of monitoring required and the frequency of inspection, measurement, and interpretation of readings. This has contributed to a certain degree of standardization in the monitoring of French dams.

For old dams with little to no instrumentation, or with lower factors of safety than are currently acceptable, an inspection of the dam and subsequent report may be ordered by the control authority. The report must include suggestions for the instruments which should be installed to improve safety, and is submitted to the Permanent Technical Committee on Dams before a decision is made/18/.

The parameters which appear to take highest priority in monitoring systems are seepage, deformations, and pore pressures/18,19/.

7.2 Instruments

Engineers in charge of the performance monitoring of large EDF dams stress that instruments yielding periodic measurements must be of simple design and construction/18/.

In the last few years, a quite wide spread trend appears to have been gaining favour in France. In brief, the trend is a systematic use of pendulums in quite large numbers in concrete dams, often accompanied by a reduction in the more error-prone, costly, and sometimes impractical topographic survey methods, made particularly difficult in high altitude sites in winter. There is also a slight noticeable trend away from extensometers for measuring dam stresses, with greater attention paid to foundation performance.

The available information on the numbers and types of instruments installed in various dams is illustrated in Table XV/20/.

7.2.1 Surface Deformations

Geodetic surveys seem to be continued for many French dams, but as stated above, the current trend is away from these surveys, due to excessive costs and difficulties in obtaining data.

7.2.2 Internal Deformations

Pendulums are becoming increasingly popular installations for the measurement of dam deformations/20/. Both optical and induction types are used, the latter being better suited to automation and installation in inaccessible parts of the dam. The precision of both these instruments is +/- 0.1 mm. In recent years, the Distofor multiple point extensometer, with precision better than +/- 0.1 mm, has been used extensively. The Clinofor inclinometer, consisting of a string of elements cemented in a borehole, and used to measure angular movements, has been used in combination with Distofors, to monitor several foundations and slides. The advantages of the Clinofor over torpedo type inclinometers are the ease and speed with which readings can be taken, the lack of potential sources of error in moving and positioning the torpedo, and the depth of hole which can be monitored without sacrificing precision. The practical precision is better than +/- 1.5 x 10^{-4} radians. The Extensofor torpedo type mobile extensometer does not appear to have been used extensively to this point in time. However, it has been used successfully, and precision over the measuring length of 1.0 or 1.5 m is approximately +/- 0.1 mm under very poor conditions and +/- 0.02 mm under good conditions/18/.

Settlements have been monitored using mercury, hydraulic, and electric settlement devices/21/. In some instances, levelling torpedoes/sondes running in subhorizontal tubes perpendicular to the dam axis, have been used. The torpedo position has been recorded by means of metal rings and an electromagnetic detector/18/.

7.2.3 Pore Pressures

Hydraulic and electrical pore pressure cells were installed in all large dams in France for many years. A preference for the electrical vibrating wire type gradually developed because of its capability of being connected to a central readout station, and its potential for automatic data acquisition. Pneumatic piezometers have also been installed in some dams but no report on their performance is documented.

7.2.4 Poorly Documented Items

It is known that the seepage, total stress, and reservoir water level have been monitored with certain instruments, but the details of the numbers and types of these instruments are not well documented. Despite the lack of explicit information, seepage appears to be of primary importance. Total stress is measured by total pressure cells in certain instances, and the reservoir water level, by water level detectors.

7.3 Measurement

Automatic data acquisition and transmission seems to be increasing in French dam monitoring systems. Instruments which have been automated successfully include pendulums, leakage measuring devices, water level detectors, and invar wire gauges. Electrical pore pressure cells, which can be connected to a central readout station without difficulty are a good candidate for automatic data acquisition in the future.

The limited data on monitoring frequency is insufficient to establish conclusions about a common practice or trend. However, Table XVI presents information which may give the reader a general idea of the order of monitoring frequency. The frequencies of monitoring instruments in the Vouglans dam during the 1st several years of operation are presented in Table XVII. Vouglans is a very large arch dam (130 m high) with a very extensive monitoring system for the time of its construction (1968-69)/18/.

7.4 Performance

Emphasis is placed on the ability of an instrumentation system to adapt to changing conditions and perceived monitoring needs. The flexibility of the system seems to depend more on the frequency of readings than on the installation of different or more extensive instrumentation/18/.

Information on the actual performance (ie success or failure rate) of different instruments is inadequate to draw any conclusions. However, it should be stated that French engineers seem to be continually looking for new ways to improve their dam monitoring systems. Recent trends include fewer and less frequent geodetic surveys, the installation of more pendulums, and the development of new instrumentation conducive to automatic data acquisition.

8.0 HYDRO QUEBEC

8.1 Philosophy

Of the 189 large dams in Quebec, approximately 75% are owned and operated by Hydro Quebec. The majority of dams built before the mid 1950's were of the concrete gravity type. After this period, the trend was toward embankment dams with an approximately even distribution of earthfill and rockfill types/22/.

The responsibility of dam surveillance in Hydro Quebec falls upon several different levels of the organization. The vice-president of production, transport, and distribution shown in the organizational chart (Table XVIII) is responsible for the implementation of the dam safety policy in the regions, and each region is responsible for its application. The dam safety directorate, under this same vice-president, coordinates the preparation of a three year program for the surveillance of dams and appurtenant structures in order to specify the content of each activity involved. Thus, the regions perform regular inspections and monitoring in accordance with the established schedules, and validate "in situ" results. The dam safety directorate issues regulations, coordinates research and development, audits the work of the regions, and coordinates periodical dam safety re-evaluations.

Monitoring devices have been installed both in dams and foundations to i) verify that the structures are behaving properly, ii) verify the design parameters, and iii) increase knowledge of the way various structures behave under different conditions/23/. The amount of instrumentation is largely dependent on the dam's risk classification.

The classification system chosen by Hydro Quebec involves the accumulation of points based upon the following criteria:

1. risk to public
2. reservoir volume
3. dam height
4. economical value of dam
5. foundation characteristics
6. type of dam
7. age of dam

Details of these criteria are listed in Appendix I.

The total of points is established by multiplying the average number of points in categories 1 to 4 by the average number of points in categories 5 to 7. The dams are then classified into the following three categories according to the number of points accumulated.

Class	Total Points
1. high risk	>30
2. medium risk	15 - 30
3. low risk	<15

Of Hydro Quebec's 189 large dams, approximately 20 - 25% are high risk, 30% are medium risk, and 45 - 50% are low risk.

The most critical times for monitoring a dam's behaviour are considered to be during construction, during first filling of the reservoir, and during the first year of operation. Emphasis is placed on the measurement of pore pressure, seepage, and displacements.

8.2 Instruments

8.2.1 Surface Deformations

The most commonly used method for the determination of horizontal displacement involves the establishment of fixed points at the extremities of the structure, and the measurement of offset distances from the straight line between the fixed points to intermediate survey marks along or close to the dam axis. When this method is not feasible or is inadequate, triangulation networks are often established with stations further from the structure. In the case of important structures, both systems are often implemented, with triangulation allowing both the measurement of displacement of several elevations of targets on the downstream face, and the measurement of vertical displacements.

Several types of instruments for measuring relative movements on the surfaces of concrete dams are also in general use. These include joint meters which are installed on expansion joints and surface fissures so that measurements may be made by use of a micrometer/25/.

8.2.2 Internal Deformations

The most common means of tying geodetic networks to deformations from internal measurements in Hydro Quebec's concrete dams is through the use of inverted and normal pendulums. Invar wires are often used to measure vertical movements as well. Normal pendulums are installed in shafts which are usually preformed in the concrete so that the cost of drilling is reduced and interference from reinforcing steel is avoided.

Several types of extensometers are presently used to measure internal displacements in both concrete and embankment dams. The vibrating chord type involves the measurement of variations in length of the chord, by a signal conditioning unit. The tubular type of joint meter is another commonly used instrument, and may be joined in continuous chains within a 4" diameter plastic pipe. Each instrument has a travel of 1-1/4" in compression and 1/4" in tension. A third type of extensometer involves the insertion of plastic tubing in a borehole, with metallic anchors disposed along the length of tubing. Each anchor is attached by a steel wire to a vibrating chord strain meter at the collar. Movements between any two anchors are detected with the use of multiconductor cable.

Torpedo type inclinometers are used to obtain simultaneous slope readings in two directions. Plastic tubing is used and telescoping joints are placed approximately 30' (9.1 m) apart. In embankment dams with earthen cores, these are generally placed vertically in the middle of the core to monitor settlements and horizontal displacements.

Finally, shear detectors have been used to determine the existence of shearing ruptures across cast-in-place concrete piles used in foundation cut off walls. Several 3' sections have been joined together in sections up to 51' long and installed in vertical pipes/25/.

8.2.3 Seepage

Simple sharp crested weirs with either rectangular or 'V' notches are commonly used to determine the quantity of leakage through a structure/25/.

8.2.4 Pore Water Pressure

Two types of piezometers are commonly used in Hydro Quebec dams to measure pore pressure. These include the open standpipe piezometer and the vibrating wire electrical piezometer, with the latter being preferred because several instruments may be installed in the same hole/23,25/.

8.2.5 Total Pressure

Total pressure cells have been installed in several structures, both concrete and embankment, to determine stresses at specific points or at contacts of two different surfaces such as concrete and foundation rock or embankment fill and abutment material/23/.

8.2.6 Temperatures

Resistance thermometers and frost penetration indicators have been installed to monitor the movements of freezing and thawing fronts within embankment dams/23/.

8.2.7 Seismicity

A program of seismic instrumentation was instituted in the Manicouagan Region of Quebec in the mid 1970's. Seismic events in excess of 2 on the Richter scale are transmitted by electric signal and telephone wires to the Division of Seismology, Department of Energy, Mines and Resources, Ottawa. The National Research Council cooperated in the installation of strong motion accelerographs and seismoscopes. One of the purposes of the network is to verify whether large reservoirs are responsible for regional microseismicity. The strong motion accelerographs also permit the analysis of dynamic behaviour of dams and the planning of corrective work in the event of stronger shocks/25/.

8.3 Measurement

The monitoring scheme for most Hydro Quebec dams usually consists of visual inspections and the gathering of instrumentation data. The frequency of measurement, in the case of instrumentation, is determined separately for each structure and for each type of instrument/25/. The minimum frequencies of inspections and instrument readings for the James Bay/La Grande project are given in Tables XIX and XX respectively. The monitoring category noted in

Table XIX is defined in terms of risk criteria, with consideration given to design details, geology and topography of the site, foundation treatment, type and size of structure, and construction conditions/23/.

Visual inspection should give particular attention to the following phenomena:

- the appearance of damp or soft zones, major seepage flows, boils, or artesian conditions at the toe of dykes or in nearby natural zones, and changes in these phenomena;

- variations in seepage or the colour of surface waters collected in different drainage or collection systems;

- the appearance or change of flow in the embankment foundation, joints or cracks in concrete structures, rock foundations or nearby slopes;

- subsidence or local deformation of crests, embankment slopes or natural terrain near the structures or along the perimeter of the reservoirs;

- the action of waves or ice on upstream slopes;

- the appearance and development of cracks;

- the penetration of frost and heaving in embankments;

- meteorological data/23/.

Note: At the time of this report, virtually no information was available on the degree of automation, the performance of instrumentation, or on detailed case studies.

9.0 BC HYDRO

9.1 Philosophy

The British Columbia Hydro and Power Authority (BC Hydro) owns and operates approximately 35 large dams, of which over 80 per cent were built before 1960. A slight majority of the large dams are of the concrete gravity type, and a combination of gravity and embankment or purely embankment types comprises most of the remainder.

Several dam failures around the world in the late 1970's led to an increased awareness of the necessity for dam safety programs/26/. The intent of instrumenting dams was to monitor performance during construction and subsequent filling, not only to detect abnormal conditions during operations which might lead to major problems, but also to obtain data for the improvement of future designs/27/.

9.2 Instruments

Most of the information in this section is taken from a report on the WAC Bennet Dam (Portage Mountain Dam) which is a 183 m high earthfill embankment/28/. Information on the numbers and types of instruments installed is outlined in Table XXI. No information on concrete dam instrumentation was available at the time of this report.

9.2.1 Surface Deformations

Survey monuments and surface settlement points are established on various berms and on the dam crest to provide information on lateral movement and settlement.

9.2.2 Internal Deformations

Vertical deformations are measured with USBR type cross arm gauges comprised of aluminum tubing and a torpedo with spring loaded pawls. Horizontal measurements are made with slope indicators (inclinometers) and with chainage measurements between displacement points in drainage tunnels. Scratch plate devices and Carlson type strain meters are also used.

9.2.3 Seepage

Seepage in each drainage tunnel is measured with a Parshall flume. At the downstream toe of the dam, rectangular sharp crested and 90^{0} V-notch weirs are installed for high and low flow rates respectively.

9.2.4 Pore Pressure

Hydraulic piezometers are used extensively in the embankment. Vibrating wire piezometers are only used in the upstream shell to monitor pore pressures during drawdown. Standpipe piezometers are extensively installed in the grouting culvert, drainage tunnels, and downstream toe. Pneumatic piezometers are used in very few instances.

9.2.5 Total Pressure

Total soil stresses are measured in the impervious core by Carlson type stress meters. These are accompanied by hydraulic piezometers so that effective stresses may be computed.

9.2.6 Seismicity

Accelerographs are used to measure seismic activity in some dams/27/.

9.3 Measurement

The monitoring frequencies and required accuracies for the various types of instruments are outlined in Table XXI. The "routine" relatively straight forward measurements and observations are usually performed by local technical personnel. More complex and sophisticated equipment is monitored by professional or specially trained technical personnel. "Intermediate" inspections are made on each dam annually or semiannually by the Civil and

Environmental Engineering Department (CEED) of the Operations Group. Special inspections, after unusual events for example, are conducted from time to time by CEED and the Hydroelectric Generations Projects Division (HGPD). The "routine" and "intermediate" inspections ensure that data is collected and that any major changes in performance are identified quickly. "Comprehensive" inspections and reviews are conducted by CEED and specialist engineers from HGPD every 5 to 7 years and involve thorough reviews of adequacy and performance in relation to design assumptions and current design criteria/26/. Since no mention is made of automatic remote reading equipment, its use is assumed to be minimal.

9.4 Performance

The performance of the various instruments is indicated in Table XXI by a comparison of the "number installed" and "number failed" columns. The loss of instruments on the whole, has been relatively small and the overall performance is considered satisfactory/28/.

10.0 ONTARIO HYDRO

10.1 Philosophy

Ontario Hydro owns and operates approximately 250 structures of which 42 are considered to be large dams by the ICOLD classification system. Of these 42 dams, 36% are greater than 30 m in height, and approximately 71% are over 30 years of age. Concrete gravity dams constitute a slight majority, and the remainder is made up of either embankment dams or a combination of embankment and concrete gravity dams. A large percentage of Ontario Hydro's 250 structures are earth dykes with heights under 15 m, used primarily for reservoir water retention.

Ontario Hydro places emphasis on the value of regular visual inspection and on the measurement of pore pressures, horizontal displacements, and seepage for evaluating the performance of both concrete and embankment structures.

Since few Ontario Hydro dams were extensively instrumented when built, emphasis is also placed on the backfitting of instrumentation into existing dams. The degree to which a structure is instrumented depends somewhat upon its structural condition and characteristics and upon its downstream hazard potential. A system was devised to prioritize Ontario Hydro's dams for the installation of instrumentation systems. Points were allotted to each structure based on the following categories as detailed in Appendix II.

Category	Weighting Factor
1. Economic Value	4
2. Hydraulic Head	4
3. Dam Age	2
4. Foundation Condition	4
5. Instrumentation Status	2
6. Performance History	3
7. Manned/Remote	1
8. Downstream Hazard Potential	5

The values for each category were multiplied by the indicated weighting factors (based on the category's significance) and totalled, to give an indication of the relative urgency for the installation of more extensive instrumentation.

10.2 Instruments

The numbers and types of instruments installed in several of Ontario Hydro's large dams are illustrated in Table XXII. The planned installation of new instrumentation and changes in current monitoring practices are identified where possible.

10.2.1 Surface Deformations

In both concrete and embankment dams, surface deformations are usually measured using two-dimensional alignment surveys and levelling. Survey monuments are placed along the crest of the structure and sometimes on the downstream slope. The survey procedure is currently being updated to incorporate triangulation and/or trilateration methods. In certain instances, survey measurements are supplemented by convergence measuring devices along the dam crest. In concrete dams, joint or crack meters are sometimes installed on the dam surfaces to measure the relative movements of blocks.

10.2.2 Internal Deformations

In concrete dams, internal deformations tend to be monitored with inverted and normal pendulums/plumblines. Most of these were not installed during dam construction and therefore had to be backfit. In several instances, the pendulums are used to "tie in" and verify survey measurements. The usual measuring instrument is a hand micrometer. In embankment dams, inclinometers/slope indicators with settlement plates are sometimes used, but their use is not extensive. Settlement profilers and gauges have also been used. Crack and joint meters are presently used sparingly in concrete lined tunnels but more extensive use is planned. Extensometers and sliding micrometers are not used in "dams" per se, but are used to monitor the movements of a rock cliff over an existing power station.

10.2.3 Seepage

The most common device used for the measurement of seepage is the V-notch weir. In certain instances, flowmeters and rectangular notch weirs are also used. Although most concrete structures have an appropriate number of seepage measuring devices, there is a general lack of emphasis on the monitoring of seepage in embankment dams.

10.2.4 Pore Pressure

Hydraulic and pneumatic pressure cells are used to monitor pore pressures in embankment dams. These cells were only installed in Ontario Hydro's more recent dams during construction. The use of vibrating wire cells is currently non existent. A more common means of monitoring pore pressures and uplift pressures is with the use of open standpipe piezometers and observation wells. In certain instances, mechanical packers have been used to

isolate a section of a borehole, and the pressure monitored with a gauge at the top of the borehole. Each of these monitoring devices can be installed in existing structures relatively easily, but drilling costs can be high.

10.2.5 Total Pressure

Gloetzl type pressure cells are the only instruments installed to measure total earth pressure, but are installed in very few dams.

10.2.6 Water Quality

Chemical analyses of seepage water are conducted in special cases where abnormal flow behaviour may indicate the dissolving of solids within the dam foundations. A comparison of upstream and downstream chemical concentrations may indicate the rate or degree of dissolutioning.

10.2.7 Seismicity

Accelerographs are used to monitor the seismic response of Ontario Hydro's hydraulic structures. Their use is limited to two dams, with two accelerographs installed in each.

10.2.8 Temperature

Thermistors and thermometers were extensively installed during construction of the majority of concrete structures built in the late 1940's and early 1950's, to monitor the curing rate of the concrete. All these instruments have since been taken out of operation.

10.2.9 Water Level

Continuous recording Foxboro gauges are used extensively to monitor the reservoir water level. In cases where automatic or continuous recording is not imperative, the water level is often measured manually from the crest.

10.3 Measurement

Automating the majority of instruments installed in Ontario Hydro's dams is not considered a high priority. Generally, it is believed that the behaviour of a dam can be checked satisfactorily by making visual inspections and manual measurements at appropriate intervals. The few devices which are presently equipped with automatic reading or transmitting capabilities are 4 extensometers, 2 weirs, 1 flowmeter, and the majority of water level measuring devices.

The frequency of measurement depends to a large extent on the status of the dam (see Appendix II for prioritizing system). Generally however, readings are taken monthly by field personnel and once or twice a year by Civil Maintenance Head Office personnel. Details of monitoring frequency for the various types of instruments are illustrated in Table XXIII. Visual inspections are to be conducted every 1 to 4 years by qualified engineers and a comprehensive inspection is to be conducted by a team of engineers approximately every seven years for major dams.

10.4 Performance

The majority of instruments which have been maintained in an appropriate manner continue to function reasonably well. These instruments include relatively new pendulums and inclinometers, simple borehole piezometers, reservoir water level gauges, and convergence measuring devices.

Unfortunately, as illustrated in Table XXIV, a relatively high percentage of instrumentation and equipment has not been maintained satisfactorily. It is believed that some of this "defective" instrumentation such as seepage weirs and accelerographs can be rehabilitated. However, instruments buried within the dam such as pore and earth pressure cells, and settlement plates cannot be rehabilitated because they are inaccessible. They have become defective not from negligence but from the poor durability of the equipment, mechanical breakdown often occurring immediately following installation.

11.0 SUMMARY OF GENERAL TRENDS

Although the design of a dam monitoring system remains a site specific task, there exist certain fundamental considerations which are common to a majority of the major dam operators considered in this report. Where possible, general trends in instrumentation philosophy, the types of instruments installed, and their average monitoring frequencies are identified and tabulated. Special attention is drawn to unusual or extraordinary practices and to dams with design and materials similar to Ontario Hydro dams. Emphasis is also placed on instruments suited to backfitting, rather than on instruments which can only be installed during construction.

11.1 Philosophy

A summary of monitoring philosphies for each country/utility is presented in Table XXV.

Monitoring schemes are generally implemented for all dams, both large and small. Extensive instrumentation systems are seldomly installed in small dams, but great emphasis is placed on the value of visual inspection. Since most failures in large dams have been identified or predicted from visual inspection, it continues to take high priority. However, legislation has generally required the installation of monitoring instrumentation to provide a systematic and more reliable means of evaluating the safety of a structure.

Generally, the monitored parameters which take highest priority in large dams are reservoir level, seepage, displacement, and pore pressure. In embankment dams, pore pressures are monitored to determine the phreatic surface and the rate of consolidation. In concrete dams, the uplift pressures at the base of the structure are used for stability analyses.

The parameters which seem to be of lower priority and are not measured as extensively are total stress, relative internal displacement, turbidity, seismic events and temperature.

The extent to which a structure is instrumented depends largely on its hazard rating or classification. Generally, all countries/utilities use some form of hazard rating system, but a few such as Hydro Quebec and Ontario Hydro have developed somewhat more elaborate systems with consideration given to the following factors:

Hydro Quebec System

1. Public risk,
2. Reservoir volume,
3. Dam height,
4. Economic value of dam,
5. Foundation characteristics,
6. Type of dam, and
7. Age of dam.

Ontario Hydro System

1. Economic value,
2. Hydraulic head,
3. Dam age,
4. Foundation condition,
5. Instrumentation status,
6. Performance assessment,
7. Manned/remote, and
8. Downstream hazard potential.

Details of these systems are given in Appendices I and II.

11.2 Instruments

The types of instruments generally used by particular countries/utilities to measure various parameters are listed in Table XXVI.

It can be seen that certain instruments seem to predominate. The measurement of seepage is usually done with V-notch weirs. Although many types of piezometers are in current use for the measurement of pore pressures, the trend seems to be toward the vibrating wire type. This may be attributed to the search for instruments which may be used in an automatic data acquisition system. Open standpipes also remain a reliable and relatively inexpensive form of piezometer. For all types of dams, surface displacements are monitored with geodetic surveys. In concrete dams, the surveys are used to verify movements detected primarily by the use of pendulums. Although many instruments are used for the measurement of relative internal deformations, the pendulums monitor movements of the dam relative to the foundation. As surveys are costly undertakings, some countries such as France, are placing more emphasis on pendulum readings. Joint meters are also commonly installed to monitor block movements. In embankment dams, settlement gauges and extensometers are often installed during construction, but borehole inclinometers seem to be the predominant form of backfitted instrumentation for measuring displacement. The installation of total stress measuring instruments must be done during construction, and since the reliability of total stress cells seems to be relatively low, no apparent trend in instrumentation practice has developed. In seismically active regions, or where large reservoirs are concerned, seismographs and/or more sensitive strong motion accelerographs are the predominant types of instruments. In concrete dams, thermometers are usually embedded within the concrete to monitor the heat of hydration of the curing concrete. In embankment and concrete dams, thermometers are sometimes lowered in boreholes to monitor the effects of temperatures on dam displacements. This is supplemental information and is not considered high priority. Finally, turbidity is usually evaluated visually and instrumentation is uncommon. These general trends in instrumentation are summarized in Table XXVII.

Unusual practices include a large degree of in situ testing on dams in Great Britain. "Traditional" methods of measuring pore pressure and lateral earth pressure in clay cores are sometimes supplemented or substituted with the use of dilatometers and hydraulic fracture tests.

11.3 Measurement

The importance of automatic data acquisition systems seems to vary from one country to another. In some instances, the inaccessibility of certain dams at various times in the year has prompted a move toward automatic remote reading devices. However, the benefits must justify the extensive costs of replacing old instruments or adding new instruments before a program is initiated.

In cases where the installation of automatic reading instruments was justified, the instruments which performed successfully were: vibrating wire piezometers, water level devices for measuring seepage and reservoir level, vibrating wire total pressure transducers, rock compression meters, thermometers, and accelerographs.

The United States Bureau of Reclamation is currently investigating the use of artificial intellegence to continually assess data as it is recorded. Dam personnel are automatically contacted when threshold values are exceeded or abnormal dam behaviour is detected. A strong commitment to automation has thus been exhibited.

The general trends in monitoring frequency and required accuracy for various types of instruments during the general operation of dams are outlined in Table XXVIII. In some cases, the range of reading frequencies is large and decisions must be made by the dam engineer(s) as to what frequency is appropriate.

12.0 RECOMMENDATIONS

In the following text, Ontario Hydro's instrumentation practices are compared with the general trends of other utilities and countries. Apparent deficiencies in our present program are identified, and ways to improve or upgrade existing instrumentation systems are recommended.

Ontario Hydro's philosophy of placing a high degree of importance on the measurement of seepage, displacements, and pore pressures is compatible with that of most countries/utilities. The measurement of seepage serves as an excellent indicator of dam performance. Increases in seepage may be indicative of developing problems within the dam, its foundation, or abutments. The sooner these changes in seepage are identified, the sooner remedial measures may be taken to reduce the risk of failure. The simplest and most effective method to date is to use seepage weirs. Weirs have been installed in many Ontario Hydro dams but in some cases poor maintenance has allowed them to become plugged with debris and thus rendered inoperable. It is believed that these plugged weirs could be restored to good working order with a relatively inexpensive "clean out" program and proper maintenance. Increased emphasis on the monitoring of seepage in embankment dams is recommended. At dams where considerable/measurable flow exists and is not already monitored, it is also recommended that new weirs be installed.

The measurement of horizontal displacements in concrete dams with plumb lines/pendulums has gained considerable support in Switzerland, Australia, France, and Quebec. Pendulums have proved to be a very reliable and accurate measuring device, and have also been used to "tie in" and verify geodetic surveys. In earth dams, horizontal and vertical displacements have commonly been measured with inclinometers/slope indicators. These have gained favour in the United States, Norway, Hydro Quebec and BC Hydro. It is thus recommended that Ontario Hydro's present program of installing new pendulums and inclinometers be continued on a case by case basis, to improve the performance monitoring to a level compatible with most other countries/utilities.

Geodetic surveys are used extensively by virtually all dam operating organizations to measure both horizontal and vertical displacements. These surveys are usually conducted using a systematic, repeatable procedure (usually triangulation or trilateration) at regular intervals. Ontario Hydro's alignment and levelling system is reasonably extensive for concrete dams equipped with pendulums but is deficient for the majority of the remaining concrete dams and for embankment dams. It is therefore recommended that the current review and upgrading of existing survey systems be continued.

The relative movements on the surfaces of concrete structures have been successfully monitored in the United States, Australia, and Quebec with the extensive use of crack/joint meters. Ontario Hydro currently uses these devices to a very limited extent in the monitoring of inspection tunnel cracks. It is believed that their use in measuring relative movements of concrete blocks would be very beneficial in evaluating the behaviour of structures. These meters are relatively inexpensive to purchase, install, and maintain, and an increase in their use where appropriate is therefore recommended.

Ontario Hydro's measurement of pore pressures using an abundance of simple, reliable standpipe piezometers and observation wells compares favourably with the practice in most countries/utilities. However, a trend toward expensive and complex vibrating wire devices is becoming more prominent internationally, to allow the addition of automatic data acquisition equipment. It is recommended that Ontario Hydro investigate further the feasibility and cost effectiveness of installing vibrating wire equipment where it might be deemed appropriate.

Ontario Hydro's monitoring frequency policies compare favourably with general practice. If structures are to be monitored and evaluated effectively, readings must be obtained as scheduled. A major change in the behaviour of a structure can occur within a period of a few weeks. For example, the seepage rate at McConnell Lake Dam approximately doubled in a one month period. The frequent operation of instrumentation and equipment also maintains the system in good working order and in most cases improves the longevity of the equipment. It is therefore recommended that monitoring frequencies be reviewed on a site by site basis at the time of annual performance and final assessment reports, and that more emphasis be placed on improved communication between Head Office and Regional personnel.

Generally the move toward automatic data acquisition and transmission is not considered an urgent necessity. However, its installation is sometimes justified when continuous readings are necessary or desirable, sites are remote and infrequently visited, or weather conditions make manual readings impossible for many months of the year. To date, Ontario Hydro has had reasonable success with its automation of weirs, flowmeters, and extensometers. It is therefore recommended that automation be implemented only where circumstances such as those listed above justify its use.

13.0 CONCLUSIONS

The original instrumentation installed during the construction of Ontario Hydro's dams is generally inadequate to monitor the overall behaviour of the structures. The present program to upgrade this old instrumentation and to install/backfit new instrumentation seems to compare very favourably with the general practices exhibited by most other countries and utilities.

Recommendations include the increased use of weirs, pendulums, inclinometers, and crack/joint meters. It is believed that much of the existing inoperative instrumentation can be rehabilitated, but that emphasis on improved maintenance must be increased.

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REFERENCES

Norway

1. Nilsen, K.Y. Di Biagio, E., Andresen, A. "Norwegian Practice in Instrumenting Dams". Water Power and Dam Construction, November 1982.

2. Myrvoll, Frank, et al. "Field Instrumentation and Performance Observations for the Vatnedalsvatn Dams". 15th Congress on Large Dams, ICOLD, Question 56, Report 56, pp 1039-1068.

Switzerland

3. Swiss National Comittee on Large Dams. "Swiss Dams - Monitoring and Maintenance:. 1985, pp 24-39.

4. Silg, Dr. B., et al. "Modern Approach to Dam Monitoring in Switzerland". 15th Congress on Large Dams. ICOLD, Question 56, Report 53, pp 985-1003.

United States

5. Leps, Thomas M. "Instrumentation and the Judgement Factor". 15th Congress on Large Dams, ICOLD Question 56, Report 31, pp 643-652.

6. Bartholomew, Charles L., Murray, Bruce C., Goins, Don L. "Embankment Dam Instrumentation Manual". USBR, January 1987, pp 2, 89, 129, 27, 54, 9.

7. Duscha, L.A. "Instrumentation for Dams". Water, Power, and Dam Construction, October 1981.

8. National Research Council. "Safety of Existing Dams - Evaluation and Improvment". National Academy Press, 1983, pp 302-306.

9. Murray, Bruce C. "Case Histories of Embankment Dam Instrumentation Automation with Satellite Tellemetry". Proceedings of 2nd International Symposium on Field Measurements in Geomechanics, 1987, pp 415-423.

10. Murray, B.C., and Browning, S.E. "Unique Monitoring of Possible Recurring Foundation Problems at Fontenelle Dam".

Australia

11. ANCOLD. "Guidelines for Dam Instrumentation and Monitoring Systems". May 1983.

12. Knoop, B.P., and Lock, L.J. "Instrumentation and Performance of Concrete Faced Rockfill Dams in the Pieman River Power Development". 15 Congress on Large Dams, ICOLD, Question 56, Report 58, pp 1103-1119.

Britain

13. Boden, J.B., Charles, J.A. "The Safety of Old Embankment Dams in the United Kingdom - Some Geotechnical Aspects". Municipal Engineer, Volume 111, No 2, February 1984, pp 46-60.

14. Kilhawy, Fred, H. "Recent Developments in Geotechnical Engineering for Hydro Projects Embankment Dam Instrumentation Performance, Engineering Geology Aspects, Rock Mechanic Studies". ASCE, New York, NY, 1981, pp 10-11.

15. Little, A.L. "Experiences with Instrumentation for Embankment Dam Performance". Field Instrumentation in Geotechnical Engineering, London, 1974, p 229.

16. Penman, A.D.M., and Charles, A. "Measuring Movements of Embankment Dams". Field Instrumentation in Geotechnical Engineering, London, 1974, p 341.

17. Hanna, T.H. "Field Instrumentation in Geotechnical Engineering". Trans Tech Publications, Fed Rep Germany, 1985, pp 659-663.

France

18. Salembier, M., et al. "Changing Composition of Instrumentation System During Operational Lifetime of Dams". 15th Congress on Large Dams, ICOLD, Question 56, Report 72, pp 1391-1414.

19. Bonazzi, D., et al. "Experience on Ageing and Maintenance of Sealing and Drainage Works in the foundations of Electricite de France Dams". 15th Congress on Large Dams, ICOLD, Question 58, Report 77, pp 1311-1327.

20. Hamon, M. et al. "Dispositifs D'Auscultation et Resultats de Mesure de Trois Barrages Francais en Beton: Avene, Le Gouet et Villerest". 15th Congress on Large Dams, ICOLD, Question 56, Report 22, p 473.

21. Courier M., et al. "Monitoring of Fill Dams. Lessons from Comparison Between Measurements and FEM Calculations". 15th Congress on Large Dams, ICOLD, Question 56, Report 74, pp 1439-1470.

Hydro Quebec

22. "Register of Dams in Canada". Canadian National Committee of the International Commission on Large Dams, 1984.

23. "The La Grande Riviere Hydroelectric Complex - Phase One Development". Societe d'energie de la Baie James. Montreal, Quebec, 1988, pp 78-79.

24. Larocque, Guy. "Operational Considerations". Maintenance of Dykes and Dams Seminar/Workshop, Nova Scotia, 1987.

25. Beaudoin, Marcel, and Brown, E.L. "Inspection and Surveillance of Dams and Associated Structures", Hydro Quebec, 1974.

BC Hydro

26. Anderson R. "Study of Dam Safety Practice and Regulations". Canadian Electrical Association, Quebec, 1985, pp 13-20.

27. Anderson R. "Study of Dam Safety Practice and Regulations. Appendix A, for CEA, Quebec, 1985, p 19.

28. Taylor, H. et al. "Embankment and Foundation Monitoring and Evaluation of Performance of a High Earthfill Dam". 15th Congress on Large Dams, ICOLD, Question 56, Report 8, pp 173-198.

TABLE I

Most Extensively Instrumented Embankment Dams in Norway/2/

Name of dam	Year completed	Maximum height m	Volume m^3	Leakage measurements	Survey monuments	Inclinometer casings	Extensometers	Piezometers in embankment	Piezometers in foundation	Total stress	Temperature
Essand	1952	?	?					22			
Møsvatn	1953	26	115 000					7			
Strandevatn	1956	40	380 000					18			
Bordal	1959	42	300 000	3	41			33	11		16
Lille Mänika	1964	15	125 000	1					11		
Hyttejuvet	1965	93	1 435 000	1	30			28		1	
Sønstevann	1966	45	502 000	1	30			6	19		
Vaslivatn	1967	25	70 000	1					8		
Kalvatn	1967	49	405 000	1	11			10		10	
Akersvann	1967	54	1 085 000	1				7		5	
Mandøla	1969	27	114 000	3	17				8		
Muravatn	1968	77	100 000	1	54				9		6
Follsjø	1969	74	940 000	4	17			8			
Gråsjø Trial Dam	1969	12	—	1	9		6	7			
Løpet	1970	17	212 000	1					10		
Svartevann	1976	129	4 715 000	1	160	8	28	30		60	8
Nyhellern	1979	85	2 616 000	1	277	2	30	16			6
Innerdalen	1981	54.5	702 000	1	82			9			
Nerskogen	1981	55	1 470 000	6	138				27		
Vatnedalsvatn S	1983	60	900 000	2	76		13	12	3	27	4
Vatnedalsvatn M	1983	125	4 200 000	1	186	4	38	29		40	5
Oddatjørn	1986/87	145	5 380 000	1	247		41	32	8		6
Storvassdamen	1987	90	9 000 000	3	284	12	30			10	

TABLE II

Instrumentation Summary for a Large Norwegian Embankment Dam/2/

Dam: Vatnedalsvatn
Height: 125 m
Type: Earthfill
Year: 1983

Parameter	Instrument	#	Method of Measurement	Performance
1. Surface deformations	Geodetic surface monuments	186	manual	excellent
2. Internal deformations	- inclinometers	4	manual	excellent
	- settlement reference plates	7	manual	excellent
	- extensometers (vibrating wire type)	38		excellent
	- USBR settlement probes (telescoping casing)			
3. Seepage	V-notch weir	1	automatic	excellent
4. Pore pressure	Vibrating wire piezometers	29	automatic	excellent
5. Total earth pressure	Vibrating wire pressure transducer	40	automatic	fair

TABLE III

Recommended Accuracies for Instrumentation in Swiss Dams

Instrument	Accuracy
Water level	+/- 10 cm
Temperature	+/- 1°C
Total Earth Pressure	+/- 5% total overburden
Plumblines/Pendulums	+/- 0.2 mm
Wire Alignment	+/- 0.2 mm - concrete 1 mm - embankment
Levelling	+/- 1 mm
EDM - Survey equipment	site specific - usually <5 mm
Extensometer	+/- 0.5 mm - concrete + /- 1 mm embankment
Crack/Joint meters - micrometers	+/- 0.05 mm
Seepage - Weirs	+/- 5% of 2X maximum discharge
Open standpipe	+/- 0.2 m
Pneumatic, Hydraulic, Electric Piezometer	+/- 0.5 m
Vertical Settlement Gauge	+/- 1 cm embankment dams only
Turbidimeter	+/- 1 ppm embankment dams only

Reference: The Subcommittee on Dam Monitoring of the Swiss National Committee on Large Dams (R. Biedermann et al) "Measuring Installations for Dam Monitoring", Wasser, Energie, Luft - Eau, Energie, Air; Vol 78 (1986) issue 7/8, pp 117-136; Vol 80 (1988) issue 1/2, pp 10-20.

TABLE IV

Instrumentation of Four Swiss Dams/3/

Dam	Grande Dixence	Mattmark	Puntdal Gal	Spitallam
Type*	G	E	A	A-G
Height (m)	285	120	130	114
Length (m)	695	780	540	285
Year Completed	1961	1967	1969	1932
Survey Monuments	36	109	72	7
Pendulums	7		5	3
Wire Alignment				15
Extensometers		22	8	
Inclinometers	38		43	
Micrometers	10			
Settlement meters		5		
Pore pressure devices		90		
Uplift pressuremeters	19		15	12-21
Total stress meters		12		
Seepage devices	1		21	36
Thermometers			72	
Performance	excellent	excellent	satisfactory	satisfactory

*Type: G gravity
A arch
E embankment

TABLE V

Comparison of piezometer types, advantages, and limitations. /6/

Characteristic	Piezometer type			
	Open-standpipe	Hydraulic	Pneumatic	Vibrating-wire
Length of time in use	Long	Long	Short	Very short
Precision of data	Moderate	Low	Low	High
Time lag in impervious soils	Long	Short	Very short	Very short
Cost — Drill hole installation	Inexpensive	—	Expensive	Most expensive
Cost — In new dam embankment or foundation	Moderate	Moderate	More expensive	Even more expensive
Construction interference in new dams	Substantial	Minimal	Minimal	Minimal
Complexity of installation	Very simple	Moderate	Complex	Moderate
Complexity of reading and maintenance	Very simple	Significant maintenance	Readings moderately complicated	Very simple
Potential for problems with installation	Fairly low	High (problems develop with age)	High	Very low
Central reading location?	No	Yes	Yes	Yes
Restrictions on central reading location?	—	Yes (elevation)	Yes (distance)	No
Time required for reading	Long	Moderate	Fairly long	Very short
Read negative pore pressures?	No	Yes	No	Yes
Other considerations	With high water levels — can have freezing problems. Porous-tube piezometer filter can plug due to repeated water inflow and outflow.	If maintenance not done regularly, lines will plug	Must prevent humid air from entering tubing	Sensitive to temperature changes

TABLE VI

Frequency Guidelines for Reading Various Instrumentation Systems[1]/6/

in USBR Embankment Dams

Instrument Type	Periodic Report-Operations	
	First Year	Regular
Hydrostatic pressure indicators	-	Quarterly
Hydraulic twin-tube piezometers (separate gauges)	-	Quarterly
Hydraulic twin-tube piezometers (master gauges)		Annually on same date as separate gauge readings
Pneumatic piezometers	Monthly	Monthly
Vibrating-wire piezometers	Monthly	Monthly
Carlson pore-pressure cells	Monthly	Monthly
Total pressure cells (vibrating-wire, pneumatic, other)	Monthly	Quarterly
Porous-tube piezometers	Monthly	Monthly
Slotted-pipe piezometers	Monthly	Monthly
Observation wells	Monthly	Monthly
Seepage measurement devices (weirs, flumes, etc)	Monthly	Monthly
Geophysical seepage measurements	As required	As required
Internal vertical movement devices	6 Months after completion	6-year intervals
Foundation baseplate settlement	6 Months after completion	Annually
Pneumatic settlement sensors	1 Month after completion	Annually
Vibrating-wire settlement sensors	1 Month after completion	Annually
Inclinometers (horizontal and vertical movements)	Monthly	Annually to semi-annually
Multi-point extensometer	1 Month after completion	Monthly or quarterly
Shear strips	3 Months after completion	Annually
Radiosonde methods	6 Months after completion	Annually
Tiltmeters	3 Months after completion	Quarterly
Embankment measurement points	6 Months after completion	3 to 6-year intervals
Structural measurement points	6 Months after completion	3 to 6-year intervals
Vibration measurement devices	Continuous readings	Continuous readings
Water quality testing	Monthly if required	Monthly if required

1 All entries indicate a minimum frequency of readings. Readings may be required more frequently (even daily) for certain installations.
2 When there are no apparent problems at the facility.

TABLE VII

Frequency of Readings for Concrete Dam Instrumentation/7/

Type Reading	Frequency
Embedded instrument	Seven to ten days during construction. Semi-monthly or monthly afterward
Deflection measuring devices	Weekly; closer intervals during periods of special interest.
Uplift pressure measurements	Monthly, except for initial filling, which should be a 7- to 10-day interval.
Target deflection and pier net triangulation measurements	Semi-annually during period of minimum and maximum air temperature. Additional measurements during early stages of reservoir filling.
Levelling across top of dam and vicinity	Periodically. More frequently in the early stages of operation and less frequently at later stages, depends on conditions encountered.

Source: US Bureau of Reclamation (1977)

TABLE VIII

Numbers of Additional Instruments
Installed at Fontenelle Dam, Wyoming/10/

Instruments	1964-65	1967	1982	1983	Frequency 1983
Survey targets	189			158	twice monthly
Piezometers					
- porous tube				17	daily
- slotted pipe				8	daily
Observation wells		27			daily
Foundation settlement devices				2	daily
Seepage devices	3		1	9	daily
Thermal probes				78	thrice weekly
Visual inspections					thrice weekly
Water Quality					weekly

TABLE IX

INDEX OF INSTRUMENTATION / MONITORING FOR CONCRETE DAMS/11/

SIMILAR MONITORING REQUIREMENTS WOULD APPLY TO CONCRETE SPILLWAYS WHICH HAVE EQUIV STORAGE FAILURE POTENTIAL WHERE SPILLWAYS INCORPORATE CONTROL BY GATING WITH POTENTIAL FOR GATE MALFUNCTION POSING A SIGNIFICANT TO HIGH HAZARD DAILY INSPECTION IS WARRANTED IN COMBINATION WITH RIGOROUS MAINTENANCE - SERVICE SHEDULES AS OUTLINED IS THE ANCOLD O.M & S GUIDELINES

SIZE OF DAM
- HT / Capacity
(Ref. Sect. 3·2 (a))

HAZARD RATING
(Ref. Sect. 3·2 (b))

INSTRUMENTATION / MONITORING SYSTEMS

CONCRETE GRAVITY, ARCH, BUTTRESS AND CONCRETE MASONRY

	SMALL						MEDIUM			MAJOR		
	5-10m >50,000m³			10-15m >20,000m³			15-100m >20,000m³			>100m >20,000m³		
	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH
1. Visual Inspection (Ref. Sect. - 8)	3-Monthly	3-Monthly	Monthly	3-Monthly	Monthly	Monthly	Monthly	Daily	Daily	Monthly	Daily	Daily
2. Seepage Measurement (Ref. Sect. - 6·1·2)		⊗ T	● T		⊗ T	● T	⊗	● S	● S	⊗	● S	● S
3. Chemical Analysis of Seepage (Ref. Sect. - 4·3)							⊗	⊗	⊗	⊗	⊗	⊗
4. Uplift Pressure Measurement (Ref. Sect. - 6·1·1)						⊗	⊗	●	●	●	●	●
5. Surface Displacement Measurement (Ref. Sect. - 4·1)								⊗	⊗	⊗	●	●
6. Internal Displacement Measurement (Ref. Sect. - 6·2, 6·3, 6·4, 6·5, 6·6.)								⊗	⊗	⊗	●	●
7. Internal Stress Measurement (Ref. Sect. - 6·7)												
8. Hydrometeorological (Ref. Sect. - 4·4)								⊗	⊗		⊗	⊗
9. Seismological (Ref. Sect. - 4·3)											⊗	⊗
10. Telemetering Automatic Recording (Ref. Sect. - 7)								⊗	⊗		⊗	⊗

LEGEND ● INDICATES MONITORING BY INSTRUMENTATION/ SYSTEM TO BE CONSIDERED

⊗ REF. NOTE 2

"Monthly" "Daily" - FREQUENCY OF VISUAL INSPECTION
"T" - INDICATES TOTAL DISCHARGE MEASUREMENT
"S" - INDICATES DISCRETE MEASUREMENT

NOTES:-
1. FREQUENCIES OF INSPECTION SHOWN ARE FOR THE 'IN SERVICE PHASE' ASSUMING DAM MOVEMENTS AND BEHAVIOUR HAVE SENSIBLY STABILIZED. DURING FIRST FILLING AND INITIAL SERVICE YEARS MORE FREQUENT INSPECTIONS APPLY (REF SECTION 9)
2. IN UNUSUAL CIRCUMSTANCES WHERE THE DAM MAY
- WARRANT CONTINUOUS STRUCTURAL MONITORING
- HAVE INADEQUATE SPILLWAY
- BE IN A HIGH SEISMIC RISK AREA
- HAVE FOUNDATION PROBLEMS (STRATIFIED FOUNDATIONS, STEEP ABUTMENTS ETC)
- INVOLVE A JUNCTION OF FILL AND CONCRETE WALLS
- BE BUILT OF UNUSUAL MATERIALS

ADDITIONAL MONITORING ⊗ TO BE CONSIDERED.

TABLE X

INDEX OF INSTRUMENTATION / MONITORING FOR DECK TYPE DAMS /11/

CONCRETE OR ASPHALT FACED ROCKFILL-WATER RETAINING MEMBRANE ON U/S FACE OF EMBANKMENT

SIZE OF DAM
– HT / Capacity
(Ref. Sect. 3·2(a))

HAZARD RATING
(Ref. Sect. 3·2(b))

	SMALL						MEDIUM			MAJOR		
	5–10 m, >50,000 m³			10–15 m, >20,000 m³			15–100 m, >20,000 m³			>100 m, >20,000 m³		
	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH
INSTRUMENTATION / MONITORING SYSTEMS												
1. Visual Inspection (Ref. Sect. – 8)	3-Monthly	3-Monthly	Monthly	3-Monthly	Monthly	Monthly	Monthly	Daily	Daily	Weekly	Daily	Daily
2. Seepage Measurement (Ref. Sect. 5·1·2)	⊗ T	● T		⊗ T	● T	● T	● T	● T	● T	● T	● T	● T
3. Chemical Analysis of Seepage (Ref. Sect. 4·3)					⊗	⊗		⊗	⊗		⊗	⊗
4. Water Table Measurement (Ref. Sect. 5·1·1)					⊗	⊗	⊗	●	●	⊗	●	●
5. Surface Displacement Measurement Ref. Sect. 4·1, 5·2·1·1, 5·5)								⊗	⊗		⊗	⊗
6. Internal Displacement Measurement (Ref. Sect. 5·2, 5·4											⊗	⊗
7. Internal Stress Measurement (Ref. Sect. 5·3)								⊗	⊗		⊗	⊗
8. Hydrometeorological (Ref. Sect. 4·4												
9. Seismological (Ref. Sect. 4·2)								⊗	⊗		⊗	⊗
10. Telemetering Automatic Recording (Ref. Sect. 7)												

LEGEND ● INDICATES MONITORING BY INSTRUMENTATION/ SYSTEM TO BE CONSIDERED

⊗ REF. NOTE 2

"Monthly" "Daily" – FREQUENCY OF VISUAL INSPECTION
"T" – INDICATES TOTAL DISCHARGE MEASUREMENT
"S" – INDICATES DISCRETE MEASUREMENT

NOTES:– 1. FREQUENCIES OF INSPECTION SHOWN ARE FOR THE 'IN SERVICE PHASE' ASSUMING DAM MOVEMENTS AND BEHAVIOUR HAVE SENSIBLY STABILIZED. DURING FIRST FILLING AND INITIAL SERVICE YEARS MORE FREQUENT INSPECTIONS APPLY (REF. SECTION 9)

2. IN UNUSUAL CIRCUMSTANCES WHERE THE DAM MAY
- WARRANT CONTINUOUS STRUCTURAL MONITORING.
- HAVE INADEQUATE SPILLWAY CAPACITY.
- BE IN A HIGH SEISMIC RISK AREA.
- HAVE FOUNDATION PROBLEMS (STRATIFIED FOUNDATIONS, STEEP ABUTMENTS ETC.)
- INVOLVE A JUNCTION OF FILL AND CONCRETE WALLS
- BE BUILT OF UNUSUAL MATERIALS.

ADDITIONAL MONITORING ⊗ TO BE CONSIDERED.

TABLE XI

INDEX OF INSTRUMENTATION / MONITORING FOR FILL DAMS/11/

ZONED FILL, EARTH AND ROCKFILL, HOMOGENEOUS DAMS, LEVEES ETC.

SIZE OF DAM
– HT / Capacity
(Ref. Sect. 3·2(a))

HAZARD RATING
(Ref. Sect. 3·2(b))

	SMALL						MEDIUM			MAJOR		
	5–10m >50,000m³			10–15m >20,000m²			15–100m >20,000m³			>100m >20,000m³		
	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH	LOW	SIGNIF	HIGH
INSTRUMENTATION / MONITORING SYSTEMS												
1. Visual Inspection (Ref. Sect. – 8)	● 3-Monthly	● Monthly	● Monthly	● 3-Monthly	● Monthly	● Weekly	● Weekly	● Daily	● Daily	● Weekly	● Daily	● Daily
2. Seepage Measurement (Ref. Sect. – 5·1·2)	⊗ T	● T	⊗ T	● S	● S	● T	● S	● S	● T	● S	● S	
3. Chemical Analysis of Seepage (Ref. Sect. – 4·3)		⊗		⊗	⊗		⊗	⊗		⊗	⊗	
4. Groundwater, Pore Pressure Measurement (Ref. Sect. – 5·1·1)		⊗		⊗	⊗	⊗	●	●	●	●	●	
5. Surface Displacement Measurement (Ref. Sect. – 4·1, 5·2·1·1)				⊗	⊗	⊗	●	●	●	●	●	
6. Internal Displacement Measurement (Ref. Sect. – 5·2, 5·4)							⊗	⊗		●	●	
7. Internal Stress Measurement (Ref. Sect. – 5·3)												
8. Hydrometeorological (Ref. Sect. – 4·4)							⊗	⊗		⊗	⊗	
9. Seismological (Ref. Sect. – 4·2)										⊗	⊗	
10. Telemetering Automatic Recording (Ref. Sect. – 7)							⊗	⊗		⊗	⊗	

LEGEND ● INDICATES MONITORING BY INSTRUMENTATION/SYSTEM TO BE CONSIDERED

⊗ REF. NOTE 2

"Monthly" "Daily" – FREQUENCY OF VISUAL INSPECTION
"T" – INDICATES TOTAL DISCHARGE MEASUREMENT.
"S" – INDICATES DISCRETE MEASUREMENT.

NOTES: – 1. FREQUENCIES OF INSPECTION SHOWN ARE FOR THE 'IN SERVICE PHASE' ASSUMING DAM MOVEMENTS AND BEHAVIOUR HAVE SENSIBLY STABILIZED. DURING FIRST FILLING AND INITIAL SERVICE YEARS MORE FREQUENT INSPECTIONS APPLY (REF. SECTION 9)

2. IN UNUSUAL CIRCUMSTANCES WHERE THE DAM MAY
- WARRANT CONTINUOUS STRUCTURAL MONITORING.
- HAVE INADEQUATE SPILLWAY CAPACITY.
- BE IN A HIGH SEISMIC RISK AREA.
- HAVE FOUNDATION PROBLEMS (STRATIFIED FOUNDATIONS, STEEP ABUTMENTS ETC.)
- INVOLVE A JUNCTION OF FILL AND CONCRETE WALLS
- BE BUILT OF UNUSUAL MATERIALS.

ADDITIONAL MONITORING ⊗ TO BE CONSIDERED.

TABLE XII

MONITORING FREQUENCIES [a] /11/

Item	Instrumentation/Monitoring System	During Construction	During First Filling	Routine Monitoring Operational Phase	Remarks
1	Visual Inspection (Ref. Sect. 8)	———	DAILY	REFER TO TABLES 3(a), (b) & (c) SECTION 3	VISUAL INSPECTIONS TO BE COMPLEMENTED BY ROUTINE INSPECTION BY ENGINEERS (Ref. Sec. 8·1 (a) (ii))
2	Seepage Measurement (Ref. Sect. 5·1·2, 6·1·2)	———	DAILY	WEEKLY (WHERE RISK/HAZARD RATING OF DAM ALLOWS LESS FREQUENT VISUAL INSPECTIONS CARRY OUT SEEPAGE MEASUREMENT IN CONJUCTION WITH VISUAL INSPECTIONS.)	A COMPLETE SERIES OF READINGS OF INSTRUMENTATION MONITORING SYSTEMS SHOULD BE TAKEN AT TIME OF ROUTINE INSPECTION BY ENGINEERS [Ref Sec. 8·1 (a)(ii)]
3	Chemical Analysis of Seepage (Ref. Sect. 4·3)	———	———	6 MONTHLY TO ESTABLISH SEASONAL PATTERN OF STORAGE / SEEPAGE CHEMISTRY. YEARLY FREQUENCY SUBSEQUENTLY.	
4	Seepage/Pore Pressure Measurement (Ref. Sect. 5·1·1, 6·1·1)	FREQUENCY AS REQUIRED TO DEFINE BEHAVIOUR UNDER INCREASING DEAD LOAD.	FREQUENCY AS MAY BE NECESSARY TO ADEQUATELY DEFINE TRENDS IN BEHAVIOUR WITH APPLICATION OF WATER LOADING / DEVELOPMENT OF SEEPAGE PATTERNS.	THREE MONTHLY [b] YEARLY [c]	
5	Surface Displacement (Ref. Sect. 4·1, 5·2·1·1, 5·5)			SIX MONTHLY UNTIL SEASONAL PATTERN ESTABLISHED THEN YEARLY	
6	Internal Displacement (Ref. Sect. 5·2, 5·4, 6·2 to 6·6)			THREE MONTHLY [b] YEARLY [c]	
7	Internal Stress Measurement (Ref. Sect. 5·3, 6·7)			THREE MONTHLY [b] YEARLY [c]	
8	Hydrometeorological (Ref. Sect. 4·4)	CONTINUOUS WHERE DIVERSION SAFETY DICTATES PREDICTION OF FLOOD INFLOWS.	———	———	CONTINUITY OF MONITORING MAY EXTEND TO SERVICE PHASE FOR MAJOR GATED SPILLWAY OPERATION
9	Seismological (Ref. Sect. 4·2)	SEISMOMETER NET ESTABLISHED PRIOR TO STORAGE FILLING	CONTINUOUS	CONTINUOUS	

(a) FREQUENCIES ARE GENERALISED. PARTICULAR CIRCUMSTANCES, ADVERSE TREND IN BEHAVIOUR OR RISK / HAZARD RATINGS MAY DICTATE MORE FREQUENT MONITORING. AFTER UNUSUAL EVENT (SUCH AS EARTHQUAKE) CARRY OUT PARTIAL OR FULL MONITORING AS APPROPRIATE.

(b) SUGGESTED MAXIMUM INTERVAL, INITIAL 3 - 4 YEARS UNTIL DAM AND FOUNDATIONS EXHIBIT STABLE CHARACTERISTICS. IT IS USUAL TO MONITOR MORE FREQUENTLY DURING RAPID DRAW DOWN (FILL DAMS)

(c) MAXIMUM INTERVAL, SUBSEQUENT YEARS, REGARDLESS OF SATISFACTORY BEHAVIOUR.

TABLE XIII

Pieman River System /12/

Dam	Height
Lower Pieman	122 m
Bastyan	75 m
Mackintosh	75 m
Tullabardine	22 m
Murchison	94 m

Number of Instruments Installed

	Mack	Tull	Murch	Bast	L. Pieman
Hydrostatic settlemnt cell	8	5	4	4	5
Survey target	20	12	6	11	9
Crest clinometer base	3				
Face slope indicator	1		1	1	1
Perimetric joint meter*	4/12	2/5	8/16	3/6	3/8
Face joint meter, pin set+	12/34	8	4	10/10	
Face strain meter*	20/39		5/20		
Embankment dilation meter	4				
Embankment pressure meter*				2/5	3/6
Foundation piezometer	14				8
Leakage weir	1	1	1	4	6

*# locations/# instruments installed in sets at orthogonal directions or in rosettes
+ # joint meters/# joint pin sets

TABLE XIV

Instrumentation of Keilder Dam, Great Britain/15/

Instruments installed in dam
(MILLMORE and MCNICOL, 1983)

Instruments	Quantity	Location	Purpose	Remarks
Pressures				
Pneumatic piezometer	47	Foundation aquifers Foundation overburden	Piezometric water levels	Low air entry High air entry
Pneumatic piezometer	9	Clay fill adjacent to culvert arch	Piezometric water levels	High air entry
Pneumatic piezometer	3	Under culvert base	Piezometric water levels	Low air entry
Hydraulic piezometer	22	Foundation overburden	Piezometric water levels	Bull-nose, high air entry
Hydraulic piezometer	72	Embankment	Piezometric water levels	Bishop type, high air entry
Bubbler piezometer	7	Foundation aquifers	Piezometric water levels	Converted standpipe piezometers
Standpipe piezometer	25	Foundation aquifers	Piezometric water levels	Casagrande ceramic tips low air entry
Pneumatic pressure cells (oil filled)	27	Clay fill adjacent to culvert arch	Total earth pressures	
Pneumatic pressure cells	15	Interface between culvert base and rock foundation	Foundation bearing pressure distribution	Installation problems

TABLE XV

Instrumentation in Various French Dams/20,18,21/

Dam	Survey Monument	Seepage	Pore Pressure	Total Pressure	Settlement Gauge	Inclinometer	Extensometer	Levelling System	Height (m)	Year Completed	Type+	Pendulum
Vieux Pre	30		64	5	3			3	79	1984	E&R	
Verney	*		22			1	2	*	42	1982	E	
Grand Maison	*						6	29	160	1984	E&R	
Rhone	*		*	*								*
Voughlans	*		*				*	*	130	1969	A	*
Gouet	20			10			51		45	1978	A	3
Villerest	19	*	*						70	1979	G	16

*Instruments are present but # is unknown
+E earthfill, R rockfill, A arch, G gravity

88-298

TABLE XVI

Frequency Data on Two French Dams/18/

Dam	Instrument	Construction	1st Filling	General Operation
Mont Cenis	all	-	-	yearly
Rhone	all	monthly on average	daily on average	monthly during 1st year
				semi annually to annually after 1st year
	Pendulums			3 to 6 months
	Levelling surveys			1 to 2 years

TABLE XVII

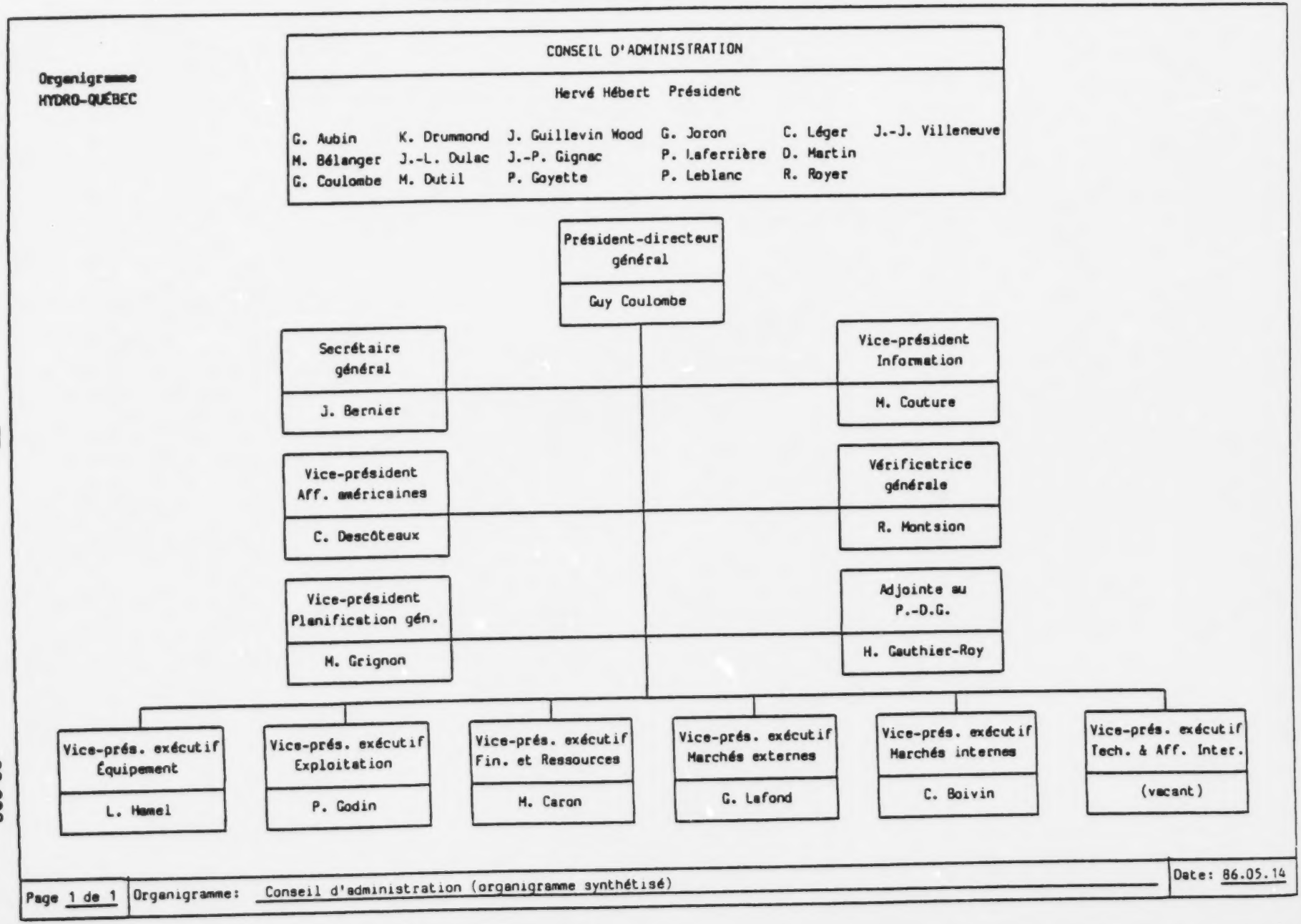
Number of Instruments and Changes in Monitoring Frequency During the Lifetime of Vouglans Dam, France/18/

Parameter or Instrument	First Filling 1968-69	1970-76	1977-78	1978-84
Horizontal disp.	38 (10)	38 (4)		
Pendulums	22 (100)	22 (26)	24 (26)	24 (26)
Levelling - arch	49 (8)	49 (2)	49 (0.5)	49 (0.5)
Levelling - foot of arch				8
Levelling - abutment	12 (8)	12 (2)		
Invar wires - galleries	6 (8)	6 (2)		
Invar Wires - foundation	20 (50)	3 (26)	3 (26)	3 (26)
Extensometers	295 (100)	295 (26)	295 (6)	295 (6)
Abutment piezometers	20 (75)	20 (26)	20 (26)	11 (26)
Arch base piezometers		2 (26)	2 (26)	9 (26)
Downstream piezometers		7 (26)	7 (26)	7 (26)
Leakage	13 (75)	14 (26)	15 (26)	15 (26)

Note: ( ) indicates number of readings per year

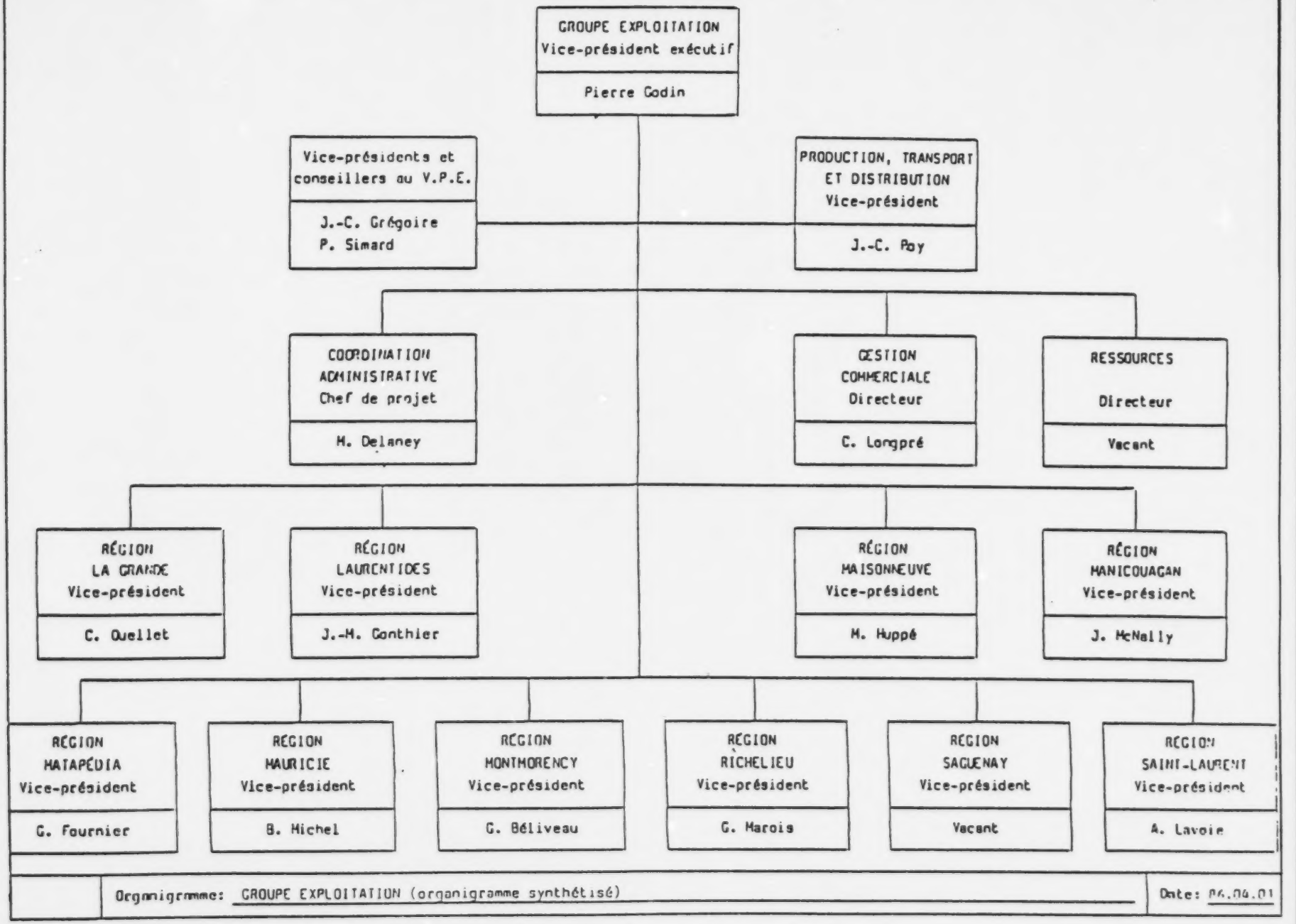
TABLE XVIII

HYDRO QUEBEC ORGANIZATIONAL CHART /24/



Page 1 de 1 | Organigramme: Conseil d'administration (organigramme synthétisé) | Date: 86.05.14

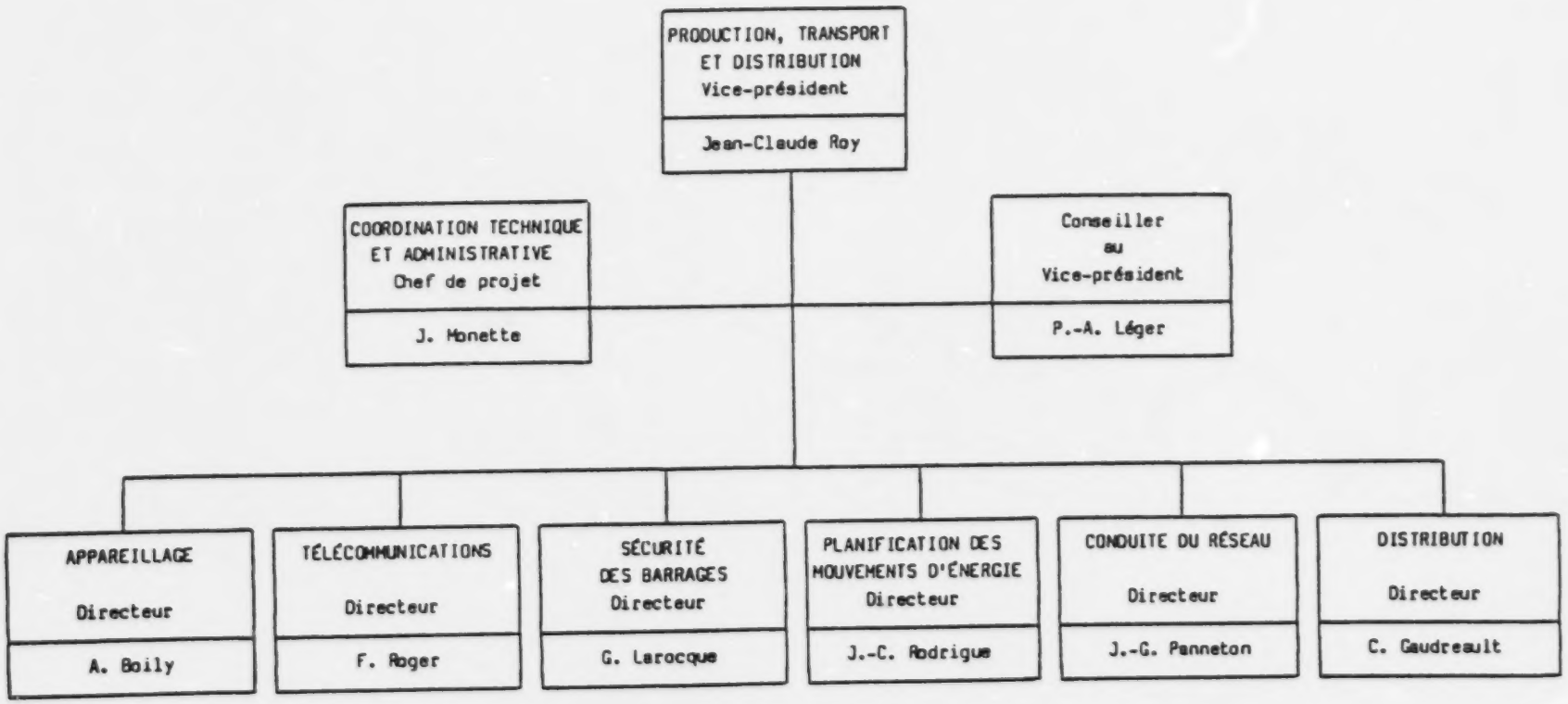
TABLE XVIII (cont'd)



Organigramme: GROUPE EXPLOITATION (organigramme synthétisé)

Date: 86.04.01

TABLE XVIII (cont'd)



Page: 1 de 1 | Organigramme: Vice-présidence Production, Transport et Distribution (organigramme synthétisé) | Date: 86.04.01

TABLE XIX

James Bay/La Grande Project /23/

Minimum Inspection Frequency for Dikes and Dams

Monitoring category	During impounding of reservoir			After impounding							
				1st year			2nd year			3rd to 5th year	
	A	B	C	A	B	C	A	B	C	A	C
Maximum (I)	2/day	2/day	1/day*	1/2 days	1/2 days	1 month	1/week	1/week	4/year	1/week	2/year
Average (II)	1/day	1 day	1/day	1/week	1/week	1 month	1/2 wks	1/2 wks	4/year	1/2 wks	2/year
Minimum (III)	1 week	1/day	1/day	2/month		1 month	1/month		4/year	1/2 months	2/year
Occasional (IV)	1/week		1/day	1/month		1 month	4/year		4/year	2/year	2/year

A Monitoring on foot
B Monitoring by vehicle
C Monitoring by helicopter
* "1/day" means one inspection per day

TABLE XX

James Bay/La Grande Project/23/

Minimum Frequency of Instrument Readings

Phase	Instrument	Sealed piezometer	Casagrande type piezometer	Inclinometer	Frost penetration indicator	Surface monument	Extensometer	Gauging weir
During construction	Work season	1/month	1/month	1/2 months	–	–	1/month	–
	Off season	1/season	1/season	1/season	–	–	1/season	–
During reservoir impounding		1/2 days	1/day	1/2 weeks*	1/month	1/2 weeks	1/2 weeks	2/week
After initial impounding of reservoir	1st year	1/week	1/week	6/year	1/month	1/month	1/season	2/week
	2nd year	2/month	2/month	1/season	1/month	1/season	1/season	1/week
	3rd to 5th year	6/year	1/month	2/year	1/month	2/year	2/year	1/month
	Subsequent years	2/year	4/year	1/year	1/month	1/year	1/year	6/year

* "1/2 weeks" means one reading every two weeks.

TABLE XXI

Bennet Dam, BC Hydro/27/

Instrument	Installed	Failed	Accuracy	Frequency
Foundation piezometer (standpipe) - Casagrand 26 (pneumatic) - air bubble 4	30	2	+/- 3 m	quarterly
Embankment Piezometers (Telemac vib wire) 8 (hydraulic) USBR 38	46	8	+/- 3m	quarterly
Stress/Strain Meters Carlson	4/11	1/2	+/- 1 unit	quarterly
Cross Arms 200-B series changed to 3 wheeled sensor 50 301 SIC	2	1	V +/- 3 mm (1 in 1000)	annually
Slope Indicators	10	1	H +/- 1 unit	annually
Surface settlement points	54	10		
Levels			12 mm/km	annually
Offsets			+/- 15 mm	annually
Displacement points	17		+/- 3 mm	annually
Survey control			4 mm/km	annually
Seepage Measurement				
Flumes (Parshall) 9" throat width	7		+/- 3 mm	quarterly
Weirs	3		+/- 3 mm	weekly

TABLE XXII

Instrumentation in Several Ontario Hydro Large Dams

Dam	Type	Height (m)	Survey Points	Pendulums	Inclin-ometers	Joint/ Crack Meters	Converg-ence Devices	Settle-ment Gauges	Piez-ometers	Pore/ Pressure Uplift Cells	Total Stress Cells	Weirs	Seismic Devices
Abitibi Canyon	E-G	106	6	4		?			14				
Stewartville	G	58	6	2					49	6		1	
Des Joachims	G	62	11	2						12			
McConnell Lake	G	37	7	2					12			4	
Rayner	G	61		4					11	36			
Pine Portage	E-G	43	26	2					10	12		10	
Otto Holden	G	34		2						22			
Saunders Main	G	47	69	4		40			27	15			
Otter Rapids	E-G	43							4				
Harmon	E-G	41	6	2					16				
Kipling	E-G	39	8	2					2	2			
Mountain Chute	G	52	15	2					10	8		2	
Lower Notch	E-G	132	33		5		?		37	30	30	8	
Arnprior	E-G	35	8		2				21			8	2
Waba	E	17	25		4			12	31		18	1	2
Cornwall Dyke	E	30	39						62				

?Instruments present but # is unknown

TABLE XXIII

Ontario Hydro Monitoring Frequencies

Instrument	Monitoring Frequency		
	Research	Regions	Civil Maintenance
Survey Points			1-2 times/year
Pendulums	Once every 3 years	Monthly	1 time per year
Inclinometers			1-2 times/year
Joint/Crack Meters		4 times/year	1-2 times/year
Convergence Devices			Once every 3 years
Settlement Gauges		Annually	1-2 times/year
Extensometers*			
Sliding Micrometer	Monthly		
Piezometers		Monthly - 2 times/year	1-2 times/year
Pore Pressure/Uplift Cells		Monthly - 4 times/year	1-2 times/year
Total Stress Cells			2 times per year
Weirs		Monthly	1-2 times/year
Seismic Devices +			
Reservoir Water Level Gauges		Continuous	

*automated - continuous reading recorded at Head Office

+automatic reading - threshold sensitive

TABLE XXIV

Ontario Hydro Instrument Performance

Instrument	Performance	Cause of Poor Performance
Convergence Measurement Devices	Good	
Survey Monuments	Fair to Good	Poor Maintenance Benchmarks on Unstable Gnd
Pendulums	Fair to Good	-
Inclinometers	Good	-
Extensometers - Sliding Micrometer	Good	-
Settlement Gauges Plate/Rings	Poor to Fair	Poor Longevity
Joint/Crack Meters	Good	
Water Level Gauges	Good	-
Pneumatic Piezometers	Fair	Leak in Lines
Hydraulic Piezometers	Fair	Leak in Lines
Sanded Tube Well	Good	-
Open Standpipe	Good	-
Observation Wells	Good	-
Weirs	Poor to Good	Poor Maintenance Debris not removed
Total Stress	Fair	Leaks in Lines Deffective cells originally
Thermistors	Good	-
Thermometers	Good	-
Accelerographs	Poor	Poor Maintenance

TABLE XXV

SUMMARY OF INSTRUMENTATION PHILOSOPHIES

Country/ Utility	Primary Reason for Monitoring	HIgh Priority Parameters	Regulatory Requirements	Important Considerations
Norway	Investigation of new designs	Seepage Deformations Pore pressures	Code of Practice	Similar materials usually used
Switzerland	Safety	Reservoir level Displacements Seepage Pore pressures	Federal Law	First filling Earthquakes Aging phenomena
United States	Safety	Seepage Surface displacements	Federal Guidelines	Engineering judgment Visual inspection Cost
Australia	Verify design assumptions Safety Determine effectiveness of remedial works	Embankment Seepage Pore pressures Concrete Displacements	ANCOLD Guidelines	Visual Inspection
Great Britain	Safety	Crest settlement Seepage	Legislated	In situ testing Visual inspection
France	Safety Verify design assumptions	Seepage Deformations Pore pressures	Legislated	Continual progress and upgrading Excessive amounts of data avoided
Hydro Quebec	Verify proper behaviour Verify design parameters Increase knowledge of dams under different conditions	Pore pressures Seepage Displacements	Corporate Guidelines	During construction 1st filling, 1st year of operation Visual inspection
BC Hydro	Safety Future designs	-	Corporate Guidelines	During construction 1st filling
Ontario Hydro	Safety Determine effectiveness of remedial works	Reservoir level Pore pressures Displacements Seepage	Standard Practice	Visual inspection Backfitting instrumentation

TABLE XXVI

General Instrumentation Practices

Parameter / Country	Seepage	Pore Pressure	Surface Displacement	Internal Displacements	Total Stress	Turbidity	Seismicity	Temperature
Norway	V-notch weir	hydraulic piezometer	Geodesy EDM equipment	Bi-axial servo-inclinometer (mechanical & magnetic) Extensometers settlement plates USBR settlement probes incased borehole	membrane press transducer oil filled hydraulic capsules			thermometers
Switzerland	V-notch weir chemical analyzers	manometers boreholes pneumatic piezometer (Gloetzl cells) - standpipes - electric piezometer	Geodesy joint/crack meter	plumblines wire alignment sliding micro-inclinometers extensometer settlement meter	total stress meter	visual turbidity meter		borehole thermometer
United States	90° V-notch weir rectangular weir Parshall Flume Velocity meters thermotic surveys self potential surveys chemical analysis	vibrating wire piezo-pneumatic piezometer observation wells	Geodesy joint/crack meter	foundation base-plates pneumatic settle-vibrating wire settlement gauge inclinometers extensometers shear strips tiltmeters	pneumatic pressure cells vibrating wire pressure cell	lab tests	seismo-graphs	thermotic surveys

TABLE XXVI (cont'd)

Parameter / Country	Seepage	Pore Pressure	Surface Displacement	Internal Displacements	Total Stress	Turbidity	Seismicity	Temperature
Hydro Quebec	V-notch weirs Rectangular weirs	Stand-pipes Vib. Wire piezometers	Geodesy wire align-ment Joint meters	Pendulums Extensometers Tubular joint meter Inclinometers Shear detectors	Total pressure cells		Seismograph Strong motion Accelero-graph	Resistance thermometers Frost pene-tration indicators
Australia	V-notch weir T pipe weir Chemical Biological analyses	Hydraulic piezometer Pneumatic piezometer Electric piezometer Uplift pressure cells	Geodesy Joint meters	Pendulums Inclinometer Tiltmeter Resistance strain gauge USBR crossarm gauge SMEC crossarm gauge Hydrostatic settlement cells Extensometers Idel sonde	Carlson stress meters		seismo-graphs Strong motion Accelero-graphs	Mercury therm ometer probes Permanent temperture meters
Great Britain	unknown	Pneumatic piezometers Hydraulic piezometers Standpipe piezometers In situ tests	Geodesy Vibrating wire strain gauge	Pneumatic settlement cells Inclinometers Extensometers	Pneumatic pressure cells			

TABLE XXVI (cont'd)

Parameter / Country	Seepage	Pore Pressure	Surface Displacement	Internal Displacements	Total Stress	Turbidity	Seismicity	Temperature
France	unknown	electric pore pressure cells	Geodesy	Pendulums inclinometers Extensometers Settlement sensors	unknown			
B.C. Hydro	V-notch weirs Parshall flumes	Standpipes Hydraulic piezometers	Geodesy	Inclinometers Strain meters	Carlson stress meters		Accelero-graphs	
Ontario Hydro	V-notch weirs	Standpipes Hydraulic pore pressure cells	Alignment levelling	Pendulums Inclinometers	Total stress cells		Accelero-graphs	

TABLE XXVII

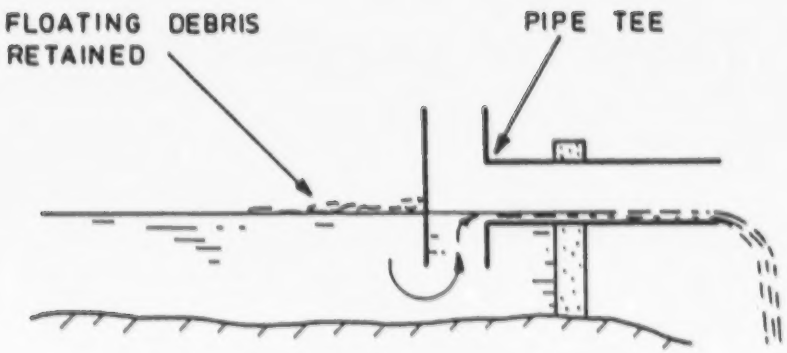
Trends in Instrumentation

Parameter	Instrument(s)
Seepage	V-notch weirs
Pore pressures	Vibrating-wire piezometer/standpipes
Surface Displacements	Geodetic surveys - joint meters in concrete structures
Internal Displacement	Pendulums (concrete dams) Inclinometers (embankment dams)
Total stress	Total pressure cells
Seismicity	Seismographs, strong motion accelerometers
Temperature	Borehole thermometers

TABLE XXVIII

Trends in Monitoring Frequency
During General Operation

Instrument	Frequency	Necessary Accuracy
Seepage measuring device	continuous - monthly	+/-5% of 2x maximum discharge
Water level gauge	-	+/-10 m
Standpipe piezometer	monthly	+/-0.2 m
Other piezometers	monthly - semi-annually	+/-0.5 m
Total earth Pressure	quarterly	+/-5% overburden
Geodetic Surveys (EDM)	semi-annually to annually	<3 mm concrete dams <5 mm embankment dams
Levelling	periodically	+/-1 mm
Plumblines/pendulums	quarterly - annually	+/-0.2 mm
Wire alignment gauges	quarterly - annually	+/-1 mm embankment dam
Crack/joint meters - micrometers	-	+/-0.05 mm
Settlement gauge	annually	+/-1 cm embankment dams only
Extensometer	monthly - annually	+/-0.5 mm concrete dams +/-1 mm embankment dams
Temperature	-	+/-1°C
Turbidimeter	-	/-1 ppm
Inclinometer	annually - semi-annually	
Seismographs	continuous	-



PIPE TEE WEIR
FOR LOW VELOCITY FLOWS

FIGURE 1

Appendix I

Hydro Quebec Risk Classification

1. Risk to the Public - This criterion represents the loss of life that could follow dam failure. A model is used to evaluate submergence and to access the population at risk

Number of People	Points
1 - 10	5
10 - 100	10
100 - 1000	15
> 1000	20

2. Reservoir Volume - The reservoir's volume is computed from the base of the dam to the maximum operating level.

Volume (10^6 m^3)	Points
0 - 1	4
1 - 50	8
50 - 1000	12
1000 - 5000	16
>5000	20

3. Height of Dam - The height is calculated as the maximum length from the lowest point of the foundation to the top of the dam.

Height (m)	Points
0 - 5	1
5 - 10	2
10 - 15	4
15 - 25	6
25 - 35	8
35 - 50	10
50 - 70	12
70 - 100	16
>100	20

4. Economical Value of Dam - This value covers the "energy value" of the dam under consideration and those located downstream. The energy value is taken as the installed capacity of the powerhouse or the value of the useful storage. The value of useful storage is calculated as the product of the optimum generation factor and the storage volume.

Installed Capacity (MW)	Point
0 - 3	1
3 - 10	2
10 - 50	3
50 - 100	5
100 - 200	7
200 - 500	9
500 - 1000	11
1000 - 2000	13
>2000	15

Energy Value of Storage (GWh)	Point
0 - 50	2
50 - 100	4
100 - 300	6
300 - 500	8
500 - 1000	10
1000 - 2000	12
2000 - 5000	14
>5000	15

Points Expressing Energy Value of Downstream Dams	Points
10	1
10 - 15	2
15 - 20	3
20 - 30	4
>30	5

5. Foundation Characteristics - This parameter takes into account the foundation material, problems detected during construction, and the nature of foundation treatment.

Rock Foundation	Points
- Igneous - no fault or particular treatment	1
- Sedimentary - no fault or particular treatment	2
- Igneous - faults or foundation treatment	3
- Sedimentary - faults or foundation treatment	4

Overburden	Points
- no treatment, no particular problem	1
- treatment of low to medium complexity	3
- particularly complex treatment	5

6. Type of Dam

Type	Points
concrete gravity	1
timber crib	2
arch and multiple arch	3
earth	4
rockfill	5

7.

Date of Construction	Points
before 1930	5
1930 - 1950	4
1951 - 1965	3
1966 - 1980	2
after 1980	1

APPENDIX II

Ontario Hydro Priority Rating Criteria

A. Structure Condition and Characteristics

The following items are quantified regarding their relative risk to the integrity of a hydraulic structure, by assigning each a value ranging from 1 to 5. A low value indicates good conditions, and a higher value reflects poorer conditions (though not indicative of immediate hazard).

1. Economic Value

The economic value of a dam is based on the annual energy generation associated with the dam.

	Energy (MWh)
1 Point -	<25,000
2 Points -	25,000 < 125,000
3 Points -	125,000 < 625,000
4 Points -	625,000 < 3,125,000
5 Points -	> 3,125,000

2. Hydraulic Head

1 Point -	<60 ft
2 Points -	61 - 120 ft
3 Points -	121 - 180 ft
4 Points -	181 - 240 ft
5 Points -	>240 ft

3. Dam Age

1 Point - less than 15 yrs
2 Points - 16 to 25 yrs
3 Points - 26 to 35 yrs
4 Points - 36 to 45 yrs
5 Points - over 45 yrs

4. Dam Foundation Condition

The foundation condition criteria are based on available information from foundation investigations. At sites where information is lacking, values are assigned based on regional geology. However a value no lower than 3 is to be assigned without site specific information.

1 Point - excellent
2 Points - very good
3 Points - good
4 Points - fair
5 Points - poor

5. Instrumentation Status

1 Point - fully instrumented structures, timber crib structures, structures under 20 ft in height.
2 Points - some additional instrumentation required
3 Points - some instrumentation installed
4 Points - very little instrumentation installed
5 Points - no instrumentation installed

0643h

6. Performance Assessment

The performance assessment is based on past inspections and monitoring information. If no inspection reports within the past 5 years are available, a value no lower than 3 is to be assigned.

1 Point - excellent
2 Points - very good
3 Points - good
4 Points - fair
5 Points - poor

7. Manned/Remote Operation

1 Point - dam located at a manned station
3 Points - dam in vicinity of a manned station
5 Points - dam in a remote location

8. Downstream Hazard Potential

The downstream hazard potential reflects the potential loss of life and economic consequences of dam failures. The downstream hazard potential rating is applied by assessing each river system, and estimating the most serious inundation hazards.

The point distribution for the downstream hazard potential is as follows:

1 Point - Hazard Category: Low

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Loss of Life:	No loss of life expected. Typically no permanent structures for human habitation inundated.
Economical Loss, Social and Environmental Impacts	Minimal economic loss such as farm buildings, limited damage to agriculture land, and minor roads. Indirect losses not significant.

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3 Points - Hazard Category:	Significant
Loss of Life:	Possibility of the loss of a few lives recognized. Typically no urban development and no more than a small number of habitable structures downstream inundated.
Economical Loss, Social and Environmental Impacts	Appreciable economic loss, including possible damage to secondary roads, minor railways, relatively important public utilities. Alternative sources of water and power available. Substantial indirect losses.

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5 Points - Hazard Category:	High
Loss of Life:	Loss of more than a few lives expected. Typically inundated downstream areas include communities or other significant developments.

Economical Loss, Social and Environmental Impacts	Excessive economic loss such as possible serious damage to communities, industrial, commercial or agricultural facilities, highways, primary roads, main railways, important utilities or other dams downstream. Dams essential for services. Major indirect losses.

B. WEIGHTING FACTORS

It is recognized that amongst the seven criteria for the structure condition and characteristics, some may influence dam safety more than others. For this reason, each is weighted by somewhat subjective engineering judgment. Table 1 lists the weighting factorswhich are utilized.

Table 1

Weighting Factors

Item	Structure Condition and Characteristic Rating Criteria							
	Economic Value	Head	Dam Age	Foundation Condition	Instrument Status	Performance History	Manned Remote	D/S Hazard Potential
Weight Factor	4	4	2	4	2	3	1	5

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The downstream hazard potential receives a weighting equal to the sum of all the weighting factors (20) for the structure condition and characteristic rating criteria. The justification for this is that it is assumed that the potential consequences of a dam failure and the characteristics and condition of a structure itself are equally important in prioritizing reviews of dam safety.